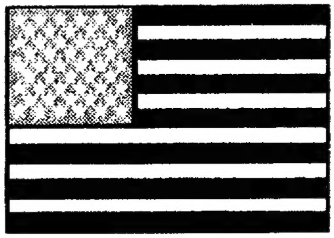

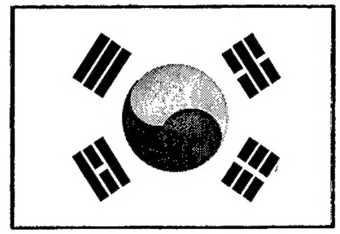

Technical Report SL-97-10
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JOINT U.S./ROK R&D PROGRAM FOR NEW UNDERGROUND AMMUNITION STORAGE TECHNOLOGIES

TECHNICAL MANAGERS'

FINAL REPORT

by

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September 1997

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Savanna, IL 61074-9639, USA
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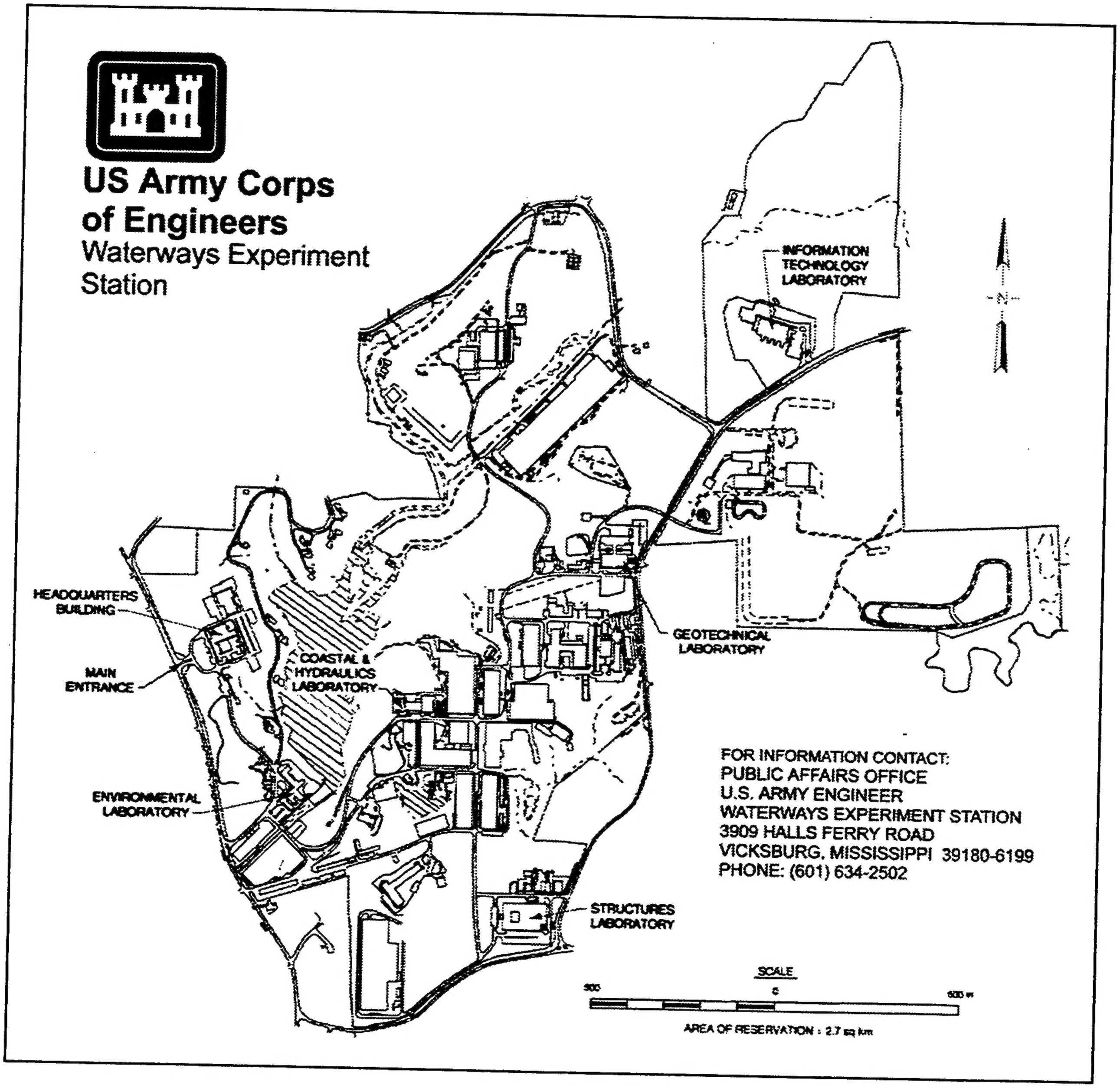

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PREFACE

This report summarizes the results of research conducted under the Joint U.S./Republic of Korea (ROK) Research and Development Study for New Underground Ammunition Storage Technologies (UAST). The UAST Program was a five-phased, 6-year research study performed as a cooperative effort between the United States (U.S.) and the Republic of Korea (ROK).

Funding for the U.S. portion was provided by the Office of the Secretary of Defense (Nunn-Quayle Amendment Project No. PE 663790, "Underground Ammunition Storage Technologies") and the Department of the Army (Project No. PE 63001/D544, "Cooperative Explosives Safety"). Funding for the ROK portion was provided by the ROK Ministry of National Defense. The Program Managers were COL Oh Dae Hwan, Logistics Bureau, ROK Ministry of National Defense, and Mr. Gary W. Abrisz, U.S. Army Technical Center for Explosives Safety. Previous ROK Program Managers were COL Jin Soo-Jun (1991-1993), COL Kim Myung Ki (1993-1994), and COL Chung Yeon Woo (1995-1996).

The lead technical agencies performing the work were the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, and the Agency for Defense Development (ADD), Taejon, Korea. The ROK Technical Manager was Dr. So-young Song, Head, Explosion Effects Division, Warhead and Ammunition Department, ADD. Dr. Lee Jun-wung was Head, Warhead and Ammunition Department, ADD. The U.S. Technical Manager was Mr. Landon K. Davis, Geomechanics and Explosion Effects Division (GEED), Structures Laboratory (SL), WES. During the period of this work, Dr. Jimmy P. Balsara was Chief, GEED, and Mr. Bryant Mather was Director, SL, WES.

This report was prepared by the U.S. and ROK Technical Managers, with the assistance of Dr. Ahn Jae Woon and Dr. Lee Jaimin , ADD, and Mr. Charles E. Joachim, GEED/WES.

At the time of preparation of this report, Dr. Robert W. Whalin was Director of WES, and COL Bruce K. Howard, EN, was Commander.

PART 1

INTRODUCTION

1.1 THE JOINT U.S./ROK R&D PROGRAM

1.1.1 Description.

The Joint U.S./ROK R&D Program for New Underground Ammunition Storage Technologies was established in 1991 as a five-year cooperative research effort between the United States (U.S.) and the Republic of Korea (ROK). The purpose of the program was to develop new design concepts for underground ammunition storage facilities that would significantly reduce the hazard distances and areas presently proscribed for ammunition storage sites by U.S. Department of Defense (DoD) (Reference 1) and ROK Ministry of National Defense (MND) safety regulations.

1.1.2 Background.

The safety hazards of concern include the airblast, debris, and ground shock produced by an accidental explosion of ammunition within a storage facility. U.S. and ROK military safety standards (Reference 1) define minimum levels of these effects, as hazard criteria, that represent significant risks of damage to inhabited buildings or injury to personnel, including those on public traffic routes. For a given quantity of munitions, described by a Net Explosive Weight (NEW), the standards provide equations or tables for distances to which these hazard levels are expected to extend from the explosion location. For example, the "Quantity-Distance" hazard criterion for airblast damage to inhabited buildings, or QD_{IB}, is defined as 0.9 psi (or 6.2 kPa) of peak airblast overpressure for NEW's of 250,000 lbs (115,000 kg) or more. The formula given in the standards to predict the distance to this pressure level is $QD_{IB} = 50\ W^{1/3}$ (or $20\ Q^{1/3}$), where W is the NEW in pounds (and Q is the NEW in kilograms). QD's are also given for ground shock and debris hazards.

Around ammunition storage sites, U.S. and ROK military safety regulations require safety hazard zones that are defined by these formulas. That is, inhabited buildings must lie beyond the

QD_{IB}, and public traffic routes (PTR's) must lie outside the QD_{PTR}. Waivers and exemptions may be granted, however, which allow temporary noncompliance with the QD requirements for strategic or other compelling reasons. For example, such waivers and exemptions were authorized for military facilities on the basis that these were temporary installations in potential war-fighting areas, where requirements for combat readiness superseded the standard safety requirements.

In the late 1980's, two events changed this situation. First, the U.S. DoD Explosives Safety Board (DDESB) determined that, after more than 30 years, the storage of ammunition at the U.S. installations in Korea could no longer be considered "temporary." The DDESB therefore stated that waivers and exemptions would no longer be granted to allow construction of new facilities (offices, housing, bowling alleys, etc.) within the QD_{IB} areas of ammo storage sites at these installations, unless positive actions were begun that would lead to conformance with the DoD safety standards.

At the same time, the ROK MND decided that, while it must continue to maintain combat readiness, greater consideration should be given to the safety of civilians, military personnel, and property around ROK military installations.

In the late 1970's and 1980's, the Korean economy developed at a rapid rate. As the nation changed from a rural to an industrialized, urban society, land values increased dramatically. Commercial and residential development also began to surround many of the U.S. and ROK military bases where ammunition is stored. These factors made the MND more concerned about the safety hazard problems around the ammunition storage sites even more critical.

In 1989, the U.S. DoD and the ROK MND agreed to cooperate in seeking a joint solution to the ammo storage safety problems. The U.S. Office of the Secretary of Defense (OSD) tasked the U.S. Army to (a) request proposals from the U.S. Army, Navy, and Air Force for such solutions, and (b) establish a joint-service committee to review the proposals and select the best

concept for development and implementation. A similar review committee was established in Korea by the MND.

Seven proposals from U.S. Army, Navy, and Air Force agencies were submitted to the U.S. and ROK committees. The proposed concepts ranged from minor modifications of existing storage methods in order to limit the size of any accidental explosions, to construction of storage facilities of entirely new designs that would greatly reduce the QD's of even very large explosions. The ROK and U.S. committees both determined (independently) that the most promising and beneficial concept was one which proposed the construction of underground magazines (Reference 2), using new design concepts that would be identified, developed, and proven effective by a joint ROK/U.S. research program.

In 1990, the U.S. Army Engineer Waterways Experiment Station (WES), which proposed the underground storage solution, and the ROK Agency for Defense Development (ADD) were then asked to prepare a Statement of Work for a joint, five-year R&D program to develop the underground storage concepts. In August 1991, a Memorandum of Agreement (MOA) was signed by the ROK and the United States (Reference 3) to authorize the execution of the program, named the Joint U.S./ROK Study for New Underground Ammunition Storage Technologies (UAST). The program was later extended by one additional year, through 1996.

The ROK R&D activities were funded by the MND. The U.S. activities were funded by OSD as a Nunn-Quayle Amendment program for international cooperation, over the first three years of the study, and by the Department of the Army over the remaining years.

1.1.3 Program Organization.

The U.S. Army and the ROK MND Logisitics Bureau both appointed Program Managers to direct the preparation of the MOA, oversee the execution of the R&D efforts in each country,

facilitate the exchange of information, and coordinate the joint planning, operation, and review of the program as it progressed. The Program Managers appointed were:

For the U.S.:	For the ROK:
Mr. Gary W. Abrisz U.S. Army Technical Center for Explosives Safety Savanna, IL	COL Jin Soo-Jun Ammunition Division, Bureau of Logistics, Ministry of National Defense

COL Jin was later succeeded by COL Kim Myung Ki, COL Chung Yeon Woo, and COL Oh Dae Hwan. COL Chung and COL Oh were the ROK Program Managers during the preparation of this report.

Technical Managers from each country were also designated to develop the research program, plan and direct the R&D efforts, and to lead the analysis, evaluation, and presentation of the results. The Technical Managers were:

For the ROK:	For the U.S.:
Dr. Song So-young Agency for Defense Development Taejon, Korea	Mr. L. K. Davis U.S. Army Engineer Waterways Experiment Station Vicksburg, MS

1.1.4 R&D Objectives.

The basic objective of the UAST Program was to develop new design concepts for underground magazines that could reduce the hazard areas (QD's) around ROK and U.S. ammunition storage sites sufficiently to conform with ROK and U.S. safety standards, without having to acquire large areas of real estate, and without adverse effects on security and operations.

Specific objectives were to:

- o Examine and evaluate design features of underground magazines in other countries for explosion hazard control.
- o Develop and test new design features.
- o Evaluate existing and develop new techniques for predicting blast effects and QD's for explosions in underground magazines.
- o Select the most beneficial design features based on QD reduction, feasibility, costs, and impact on operational readiness.
- o Proof-test the design features and QD prediction techniques as necessary through large-scale tests.
- o Develop engineering design concepts for construction of underground magazines.
- o Make recommendations to the U.S. DoD Explosives Safety Board and the ROK Explosives Safety Management Board for changes to QD criteria and formulas in the U.S. and ROK safety standards, based on the R&D results.

Although it seemed clear at the beginning of the program that underground storage would provide some significant reductions in QD's from those associated with other types of storage, there were many unknown factors involved in such a complex problem (for example, blast propagation through underground facilities), along with technical risks that were inherent in the R&D effort. However, the U.S. and ROK Technical Managers estimated that a 90-percent reduction in the QD areas, compared to those defined by the current safety standards for existing, above-ground magazines, was possible if the program was completed successfully.

1.2 R&D Plan.

The original joint R&D program was designed to be performed in five phases, with roughly one-year durations for each phase. These phases, and the major tasks to be accomplished in each phase, were:

Phase 1: R&D Preparation and Planning

- Review and analysis of previous R&D related to the blast effects produced by explosions in underground magazines.
- Assessment of ROK and U.S. ammunition storage requirements in Korea.
- Alignment of U.S. and ROK research procedures, including test methods, computational techniques (computer models), and magazine performance criteria (for hazard reduction).
- Acquisition of testing equipment and new computer codes.
- Design and construction of model structures for small-scale tests in the ROK and U.S.

Phase 2: Small-Scale Test Program

- Conduct of small-scale explosive tests to investigate effects of different tunnel-chamber design features on the internal and external blast levels.
- Initial computer model calculations to simulate explosion blast effects in different magazine designs.
- Evaluation of underground ammunition storage feasibility and benefits at U.S. Army installations within the continental United States.
- Based on the results of Phase 2 research, down-selection of design features for further investigation in Phase 3.
- Development of test designs for Phase 3.

Phase 3: Intermediate-Scale Test Program

- o Completion of a joint U.S./ROK report on the Phase 2 program.
- o Construction of underground test facilities for ROK and U.S. intermediate-scale tests.
- o Performance of intermediate-scale tests.
- o Detailed computer modeling studies.
- o Survivability evaluation for underground magazines subjected to enemy attack.
- o Based on the results of Phase 3 research, down-selection of design concepts for final recommended magazine designs.
- o Development of a test plan for a final Validation Test.

Phase 4: Validation Test

- o Completion of a joint ROK/U.S. report on the Phase 3 program.
- o Completion of reports of supporting studies.
- o Performance of the Validation Test.
- o Evaluation of Portal Barricade Effectiveness.
- o Development of technology transfer plan for transition of R&D results to engineering designs and revisions of safety regulations.

Phase 5: Engineering Design Concepts

- o Analysis of the Validation Test results.
- o Completion of a joint U.S./ROK report on the Phase 4 program.
- o Development of basic engineering designs for underground magazines.

- Submission of recommendations to DoD and MND for revision of safety standards for underground magazines.
- Completion of a joint ROK/U.S. final report.
- Determination of construction engineering and operational requirements for underground magazines.

PART 2

BACKGROUND

2.1 PROBLEM DESCRIPTION

2.1.1 Hazards From Accidental Explosions in Underground Magazines.

a. General. Military ammunition supplies are normally stored in above-ground structures--most commonly in earth-covered magazines (ECM's). If the ammunition in a storage facility accidentally explodes, serious safety hazards may extend out to distances of hundreds, perhaps thousands, of meters, depending on the size of the explosion. The size is defined by the Net Explosive Weight, or NEW, that is involved in the explosion. NEW's in ECM's may range from a few kilograms to 200,000 kg or more.

A large explosion will blow an ECM completely apart. The main types of hazards produced are airblast, debris (which includes munition fragments, as well as structural debris from the ECM), and ground shock. The following sections describe the nature of these hazards when such explosions occur in underground magazines.

b. Airblast. When an explosion occurs on the ground surface, an airblast shock front will expand in a hemispherical fashion from the center of the detonation. As the shock front passes a given location, the overpressure will quickly (in a few milliseconds or less) rise to a peak value, then decay exponentially over a much longer period (normally, tens to hundreds of msec.). When a detonation occurs below the ground surface, less airblast is produced because of the energy expended in blowing away the soil (or rock) above the detonation, which allows the airblast pressures to escape into the air. If the detonation occurs below a depth called the "containment" depth, the explosion may be completely contained underground, with no airblast produced.

This also applies to explosions in underground magazines. If the munitions storage chamber is near the surface, the rock cover can be blown away (or "breached") to release the explosion blast pressures in the storage chamber. The released airblast produces a circular hazard area, extending from the center of the cover breach to a distance where the airblast peak pressure has attenuated below a critical damage level. If the thickness of the rock cover over the storage chamber is equal to or greater than a critical cover thickness (C_c), the mass of the cover will be too great to be lifted by the gas pressure, and a cover breach will not occur.

All underground magazines have access tunnels to reach the storage chamber from an outside entrance. When a detonation occurs in a storage chamber, an airblast shock front will travel into the tunnel, followed by a strong flow of the detonation gases that is driven by the high pressures in the chamber. The shock front tends to expand directly outward from its source, reflecting off surfaces it strikes and refracting around corners. The detonation gas pressures, on the other hand, tend to flow equally well in any direction where the ambient air pressure is less than the gas pressure. When the airblast front in the access tunnel reaches the tunnel portal, both the shock and gas pressures quickly expand into the "free air" outside.

Obviously, a rapid release of airblast through an access tunnel can bleed off the pressures in the storage chamber, thereby reducing the probability of a cover breach. This may reduce the critical cover thickness, depending on the rate of release. Conversely, a shallow cover thickness may allow a rapid breach of the cover, which could theoretically reduce the blast effects (and hence, the hazard distances) emanating from the tunnel portal.

Many small underground magazines operated by the British navy were designed on the latter concept; i.e., that breaching of the cover would reduce the normally farther-reaching airblast hazard distance from the portal. Figure 2.1 shows a half-scale version of this type of magazine, constructed at China Lake, CA in 1988 (Reference 4) as a project sponsored by the Klotz Club to test this design theory (Note: The Klotz Club is an informal committee of representatives from France, Germany, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom, and the United States, which addresses R&D issues associated with ammunition storage safety).

Unfortunately, the test showed that the breach of the chamber cover occurs much too slowly to have a significant effect on the tunnel pressures (Reference 5). As shown in Figure 2.2, the airblast QD was still found to be significantly less than the existing standards indicated.

c. <u>Debris</u>. When ammunition explodes in a storage chamber, fragments from the munition casings will impact the walls and ceiling of the chamber almost instantly, thus transferring their momentum energy into the structure. In an ECM, this energy, together with the airblast shock, can shatter the structure into rubble. The detonation gas pressure then accelerates the debris, often enough to throw it hundreds of meters. The impact of munition fragments against the rock walls of an underground chamber should produce very little secondary debris. Some fragments will fly in the direction of the chamber access tunnel, however, and many of those which struck the walls and ceiling will be carried down the tunnel by the strong flow of the detonation gases, along with pieces of packaging, rock or concrete broken loose by the blast, and other debris.

Rock debris created from breaching of the chamber cover produces a debris hazard over a more-or-less circular area but, except for very shallow magazines, normally within a radius of 100m or less. The debris blown from the access tunnel portal, on the other hand, will be confined to a fairly narrow sector (20 degrees each side of the extended tunnel centerline, according to present safety standards), but may exit at a very high velocity. Consequently, the QD for the portal debris may be 500 m or more. For this reason, the simple magazine design shown in Figure 2.1, with a straight access tunnel, is called the "shotgun" type of underground magazine.

d. <u>Ground Shock</u>. For an above-ground explosion, the impact of the airblast shock against and along the ground surface couples energy into the earth, which travels downward and outward as an expanding ground shock wave. The portion of the ground shock traveling near-horizontally, at and just beneath the ground surface, may be manifested in the form of horizontal or vertical surface motions, similar to the seismic motions from an earthquake. The current safety standards use a particle velocity of 23 cm/sec as a ground shock hazard criterion.

Similar effects are produced by an explosion in an underground magazine, except that the initial confinement of the detonation (even if the chamber cover is breached) results in a greater portion of the explosion energy being transferred into the surrounding rock as ground shock.

e. **Explosion Propagation**. Individual above-ground magazines, such as ECM's, must be separated by an intermagazine distance sufficient to ensure that a detonation of one (the "donor") will not propagate a detonation to an adjacent ("acceptor") magazine. Such a propagation can occur if the blast pressures or debris from the donor detonation impact any munitions at the acceptor location with enough force to cause them to detonate.

Between adjacent underground magazines that each have an outside entrance leading to a single storage chamber, the propagation of an explosion from one magazine to the other is extremely unlikely. For underground magazines with multiple, interconnected storage chambers, however, the risk of propagating a detonation from a donor to a nearby acceptor chamber must be considered. If a "prompt" propagation occurs (i.e.; within a time interval of one second or less), the blast effects from the second detonation may reinforce those of the first detonation, thus producing greater hazard distances.

Prompt propagation in multi-chambered underground magazines can occur by at least two methods. First, a strong ground shock may travel through the rock between chambers and cause pieces of rock to spall off the wall of an adjacent chamber. If the spall debris impacts munitions in the adjacent chamber with sufficient force, a detonation may be initiated. Secondly, the tunnel passages between storage chambers will confine and channel explosion blast pressures, so that the pressures produced at the entrance of an adjacent chamber may be much higher, and of much longer duration, than those at a similar distance from an above-ground explosion. If a blast wave of sufficient strength enters an adjacent chamber, its impact against munitions in the chamber can potentially produce dynamic stresses that will cause a detonation.

2.1.2 Hazard Prediction and Mitigation/Control Concepts.

a. General. The advantages of underground ammunition storage, as opposed to above-ground storage, in reducing explosion hazard distances were expected to stem from three sources. First, as shown in Figure 2.2, the airblast and debris hazard areas for the "worst case" type of underground magazine (i.e., the simple "shotgun" design) had already been proven by the 1988 Klotz Club test at China Lake, CA to be smaller than those from an above-ground ECM. Secondly, it was believed that investigations of more complex underground magazine designs would show that the hazard prediction formulas used in the present safety standards are overly conservative. The development of refined hazard prediction formulas would allow further reductions of the hazard areas for underground magazines. Thirdly, the results of research by WES and others over the last 20 years or so indicated that underground magazines could be constructed with special features that would mitigate or control the hazards which are of greatest concern--particularly airblast and debris. These features include such concepts as blast traps, expansion chambers, chamber closure devices, portal barricades, etc. The following sections describe the issues related to hazard predictions, and the concepts for hazard mitigation, that were investigated in the UAST program, grouped according to their location within the underground system.

b. In the Storage Chamber. No formulas are given in the existing safety standards to predict the peak airblast pressures within a storage chamber in which a detonation occurs. While there is no direct need to calculate such pressures, there is an indirect need, in the sense that the chamber pressure is the source of almost all other hazardous effects. Therefore it is important to define how the internal pressures vary as a function of the amount of explosive involved (i.e., the NEW), the chamber loading density (i.e., the weight of explosive per unit volume of the chamber), the characteristics of the munitions, and other factors.

The existing standards do provide a formula for the critical chamber cover thickness, C_c (in feet), that is required to ensure that the debris throw from a rupture of the cover does not exceed a "negligible" amount. The formula is

$$C_c = 2.5W^{1/3} \tag{2.1}$$

where W is the NEW, in pounds. Similarly, the standards say that external airblast will be negligible if the cover thickness is greater that $0.75W^{1/3}$. For the UAST program, however, it was assumed that the chamber cover thickness would always equal or exceed the critical cover thickness, so airblast and debris from a cover rupture could be eliminated from concern.

Two principal concepts were investigated as potential methods for confining explosion hazards to the storage chamber. These included:

(1) Chamber closure devices. In the 1970's, the Klotz Club conducted a large-scale test of the Swiss-designed Klotz Block, which is a large, wedge-shaped block of heavily-reinforced concrete located just inside the entrance to a storage chamber (Reference 6). The Klotz Block is moved by a hydraulic piston, so that it can be pushed into the chamber access tunnel, like a cork in a bottle, to keep the chamber sealed in the event of an explosion (Figure 2.3). To allow access, the block is hydraulically moved back into the chamber. If in the open position when an explosion occurs, however, the block would be driven closed by the blast.

The UAST program had strong interests in developing a similar chamber sealing method, but one which would be much less expensive to build, and would normally remain in an open position, to be driven closed only by an explosion.

(2) Self-sealing chambers. Theoretically, it seemed possible that storage chambers and their entrance tunnels could be designed so that a large detonation in the chamber could push a weak section of the chamber wall into a void beyond the wall. If the void happened to be a section of the entrance tunnel, the explosion might cause the chamber to seal itself by blocking the tunnel. The feasibility and performance of such "self-sealing" chambers was included as an area of investigation.

c. **Between the Chamber and the Portal**. The existing safety standards provide a formula for peak airblast overpressure P_w (in psi) at a tunnel "opening" (i.e., at the portal) as a function of W, and the total volume of the underground system that is available for gas expansion, V_t, in ft^3:

$$P_w = 895\ (W/V_t)^{0.45} \tag{2-2}$$

The metric equivalent, using kPa, kg, and m^3, is

$$P_w = 1{,}770\ (Q/V_t)^{0.45} \tag{2-2a}$$

It logically follows that this formula should predict the pressure at any point in the tunnel system, as long as the volume not filled by gas expansion beyond that point was subtracted from V_t. Since this was not explicitly stated, however, better information was needed to define and verify an equation that would predict the peak pressure at any location. This information was needed, for example, to predict the maximum loading on blast doors at the entrances to adjacent chambers.

Figure 2.4 shows some of the concepts for controlling airblast and debris that were proposed for investigation in the program. These included:

(1) Blast traps. These are short, dead-end sections of tunnel located at a tunnel bend or intersection. In principle, both the airblast shock front and debris blown down the tunnel will tend to travel straight into the bend or intersection, and impact the back wall of the trap. The shock wave will lose energy as it reflects back toward its source, and the debris will be caught in a "dead" spot and fall to the floor of the trap. The extent to which blast traps would reduce the total airblast and debris levels was not known, however, nor was the optimum size or location of the trap.

(2) Expansion chambers. An expansion chamber is simply a large room along the tunnel route. It was expected to reduce blast pressures beyond the chamber by allowing the shock front to expand into the room as it entered, then lose energy by multiple reflections off the chamber

walls. In addition, the gas pressures would expand into the volume of the chamber, providing a proportional reduction in pressure (see Eq. 2-2). It appeared that expansion chambers would also serve as excellent debris traps, as long as the tunnel sections entering and exiting the chamber were not in alignment. As with blast traps, however, the actual effectiveness of expansion chambers, and the influence of their size, shape, and location were not known.

(3) Tunnel bends, intersections, and constrictions. For a "shotgun" magazine, the airblast and debris blown from the storage chamber by a detonation has a straight, unimpeded path to the tunnel portal and the outside world. Both logic and science (e.g., the flow of fluid through pipes) indicate that anything which impedes, disrupts, diverts, divides, or constricts the flow of airblast and debris through an access tunnel should reduce the intensity of those effects (due to energy losses) at the tunnel portal. A portion of the R&D effort was designed to investigate and quantify such reductions.

(4) Tunnel wall roughness. From the field of engineering hydraulics, it is well known that fluids move more efficiently through smooth-walled pipes than through those with rough walls. A portion of the R&D effort was directed toward a study of the effect of tunnel wall roughness on the movement of airblast and debris through the tunnels. This question was also an issue for using the results of small-scale tests in smooth-walled, model tunnels to predict blast effects in actual tunnels in rock.

d. At the Portal and Beyond. Equation (2-2) gives the predicted peak airblast overpressure, P_w, at the tunnel portal, according to the existing U.S. safety standards. The standards also give an equation for the distance R beyond the portal, along the extended tunnel centerline, to a given peak overpressure, P_{so}, as a function of P_w and the minimum hydraulic diameter, D, of the tunnel at or near the portal. The equation is

$$R = D/(P_{so}/P_w)^{0.74} \tag{2-3}$$

where R and D are in feet and P_{so} and P_w are in psi.

For an external point located θ degrees off the extended tunnel axis, the distance is

$$R = D/(P_{so}/P_w)\,(1 + (\theta/56)^2)^{0.74} \tag{2-4}$$

The accuracy of these formulas was not known.

Hazard mitigation concepts at the portal and beyond included:

(1) Portal barricades. The existing standards predict the hazard range for debris blown from a tunnel portal as simply 2,200 ft (670m), over an area extending 20 degrees to either side of the extended tunnel centerline. The standards state that these values apply "unless positive means are used to prevent or control debris throw." One of the most obvious means of doing so is the use of a berm or barricade to intercept debris in front of the tunnel portal. In addition to the effect on debris, it was also desired to see if a portal barricade might have any effect on airblast hazard distances.

(2) Multiple exits. Another issue was the effect of having two or more tunnel exits, rather than one. Logic suggests that, if one exit is replaced by two, the amount of blast energy issuing from either of the two must be less than that from the single exit. However, a recent (1992) revision of the U.S. safety standards deleted the benefit attributed to multiple exits in the previous version. This issue needed to be clarified and quantified.

2.1.3 Previous Research.

a. Early Work. The storage of military ammunition and explosives has presented a safety problem since explosives were first used for military purposes. In earlier times, however, the relative importance of safety was much less than it is today (Reference 7). It is known that underground magazines were used to store ammunition and explosives in the nineteenth century. The earliest known (to the authors) research effort directed toward the reduction of safety hazards from an accidental explosion in an underground magazine was performed in 1895 (Reference 8). An experiment was conducted at Blanzy, France involving the detonation of 500 kg of dynamite in an underground chamber to test the performance of a blast-driven chamber closure block, constructed of wood and cardboard. The test was successful.

In 1936, the "Riedel" test was conducted in Germany, from which the Norwegians developed design criteria for underground magazines they constructed in 1945-1955 (Reference 9). Extensive additional research was performed in Norway in 1966 (Reference 10) after a large, accidental explosion occurred in an underground storage facility in Finland in 1965.

b. <u>The Klotz Club</u>. Also in 1966, the concept for a fast-acting chamber closure device, called a "Klotz," for underground magazines was developed by the Norwegian Defense Construction Service and the Swiss firm of Basler & Hoffman (Reference 6). In 1972, representatives of the defense ministries of Norway, Switzerland, Germany, and Sweden agreed to jointly carry out a full-scale proof test of performance of the Klotz Block in a simulation of an accidental magazine explosion. The test was conducted at Älvdalen, Sweden in May 1973.

In 1975, the Klotz Club was established as an unofficial, *ad hoc* organization when the four countries agreed to continue coordination and cooperation of research on ammunition storage safety. The United Kingdom joined the Club in 1977, the U.S. in 1984, France in 1990, and the Netherlands in 1996. The Klotz Club collectively sponsored large-scale experiments to investigate accidental explosion effects in underground magazines at Älvdalen in the 1980's, and the "shotgun" magazine test at China Lake, CA in 1988 (Reference 11). The Klotz Club also supported the development of advanced computational models to predict hazards from such explosions in the early 1990's.

c. <u>Other Research</u>. Throughout the 1970-1990 period, independent research efforts on blast effects from underground magazines continued, particularly in Norway, but also in Switzerland, Germany, Sweden, the U.K., and the U.S. Most of this work involved tests with small-scale models or shock tubes to refine predictions of airblast hazard distances. However, some efforts were made to investigate blast mitigation techniques (expansion chambers, barricades, etc.) or other subjects, such as debris hazards, ground shock, and critical cover thickness.

In 1990, WES proposed to the Eighth U.S. Army (EUSA) that an underground ammunition storage facility be constructed at Camp Stanley, Korea as a solution to the problem of excessive hazard areas (from a potential accidental explosion) around the storage area for uploaded ammunition supply trucks of EUSA's 2nd Infantry Division. In addition, such a facility would also protect the exposed trucks from enemy artillery fire or air attack. The facility was constructed in 1993.

The Camp Stanley underground facility is unique, in that it stores ammunition loaded on trucks and trailers, rather than in bulk storage. In 1991, WES constructed a 1/3-scale section of the Camp Stanley facility at a site in Colorado, and conducted airblast and debris hazard investigations by simulating accidental detonations of truckloads of ammunition. The results were used to verify the protection provided by the Camp Stanley facility against explosion hazards, and the reduced QD areas (Reference 12).

d. Literature Reviews. As an early part of the UAST program, a thorough review and analysis was made of available technical papers, reports, and other sources of information covering previous research related to explosion hazards from underground magazines (Reference 13). The purpose was to define the "state-of-the-art" at the beginning of the joint US/ROK effort, in order to develop the most productive R&D plan and approach.

2.2 R&D APPROACH

Because of the large scope of research required, the UAST study was subdivided into five phases, of roughly one year duration each. Phase 1, in the first year, was devoted to developing a more detailed plan for the main R&D efforts, gathering and evaluating important background information, and acquiring the equipment and developing the skills required for the project. Phase 5, in the last year, was devoted to "technology transfer" of the research results, in the form of recommendations for revisions of safety standards, design drawings for underground magazines, and a final report.

The main R&D effort was carried out in Phases 2, 3, and 4. Most of the research involved investigations of explosion effects phenomenology for underground magazines. Both experimental and calculational modeling techniques were used, as described in the following sections. The remainder of the R&D effort consisted of supporting studies to (1) develop information needed as input to the phenomenology studies, (2) supplement the main R&D thrusts, or (3) support the application of the research findings.

2.2.1 <u>Experimental Program</u>.

The experimental program consisted of three parts. First, a wide range of small-scale experiments was conducted (Phase 2 of the program) to establish basic relationships between the magazine designs, detonation conditions, and the characteristics of the blast effects produced, and to investigate promising methods for control or mitigation of those effects. In the next stage (Phase 3), "intermediate"-scale tests were performed to refine these relationships and test the most promising hazard control concepts under more realistic conditions. The third stage was a large-scale "validation" test, to confirm and demonstrate the findings of the previous stage. Additional details are given below.

a. <u>Phase 2: Small-Scale Tests</u>. The U.S. and ROK small-scale tests conducted in Phase 2 were mainly designed to investigate airblast phenomena. The analysis of prior research showed that airblast in confined areas, such as underground tunnels and chambers, has two components--the initial air shock front, including secondary reflections, and the gas pressures created by the detonation products. A number of design features for control of blast hazards in underground magazines had been investigated, to a limited extent, in the previous research. Some investigations had been made by the U.S. Army Ballistics Research Laboratory (BRL), and others by Switzerland and Norway. Most of this work is described in the UAST literature review and analysis (Reference 13).

The small-scale tests conducted in Phase 2 of the UAST study were designed to provide more extensive and reliable measurements of how the shock and gas pressure propagation was influenced by many of the magazine design features that were examined in the earlier research, as

well as by additional features that might prove effective in reducing the blast pressures that emerged from the tunnel exits.

b. <u>Phase 3: Intermediate-Scale Tests</u>. It was recognized at the inception of the UAST Program that explosion tests would have to be conducted in actual underground environments in order to obtain data that could be applied, with reasonable confidence, to full-scale magazines. Phase 3 of the program consisted of experiments conducted at an intermediate scale at test sites in the U.S. and the ROK. The test scales of 1/8 for the ROK series, and 1/3 for the United States series, were largely based on the economics of constructing the required tunnels and chambers in rock at the two sites. The tests conducted in Phase 3 were carefully selected as those most important for (1) verifying the results of small-scale tests (or computer simulations), (2) assessing the influence of an actual underground environment on findings developed from the small-scale tests, or (3) investigating phenomena that could not be modeled with small-scale tests.

c. <u>Phase 4: Validation Test</u>. In the original R&D plan for the UAST program, it was anticipated that both the U.S. and ROK intermediate-scale tests would be conducted at test scales of 1/6 to 1/8. To validate the results of these experiments, a final test at a larger scale would be necessary. Therefore the Phase 4 Validation Test, to be conducted at 1/3-scale, was planned as the concluding test effort.

After detailed planning for the Phase 3 program began, however, it was found that the U.S. intermediate-scale tunnels and chambers could be more economically constructed at 1/3-scale than at 1/6-scale. There would be little benefit, therefore, in designing the Validation Test to repeat any results of the U.S. Phase 3 series conducted at the same scale. Consequently, the purpose of the Phase 4 Validation Test was changed somewhat, to have a main objective of testing, at large scale, the ROK-designed chamber closure block (the Magae Block), which had been evaluated at 1/30 and 1/8-scale in the ROK Phase 2 and Phase 3 programs.

2.2.2 Computer Simulations.

a. Application. Over the last ten years or so, the rapid advance of high-performance computers has allowed the development of much-improved calculational models of explosion effects. An extensive series of computer simulations were performed in the UAST program to supplement and extend the experimental data, particularly in regard to airblast phenomena. These simulations provided insights into the performance of such concepts as expansion chambers, multiple tunnel exits, etc., as well as the effect of tunnel geometrics, tunnel wall roughness, and other factors.

b. Computer Programs.

(1) First-principle codes. During Phase 2, several first-principle, finite-difference, hydrodynamic computer codes were examined for use in the UAST program. Two of these, HULL and SHARC, were selected for detailed evaluation by both ADD and WES (Reference 14). Airblast levels in underground tunnel/chamber geometries were calculated with the two codes and compared to experimental data. Although the calculated wave forms were very similar, SHARC required less detailed gridding of the problem, and predicted shock arrival times with greater accuracy. The SHARC code was therefore used by WES, ADD, and contractors for most of the airblast calculations in the remainder of the program.

(2) PC-codes. The basic PC (personal computer) code used in the UAST program was BLASTX (Versions 3.0 and 3.5). This is a relatively simple, fast-running program that calculates peak airblast pressures in confined areas by the ray-tracing method. It was used to predict peak pressure levels for gage selection and ranging prior to each test in the Phase 3 intermediate-scale series. Since, in most cases, BLASTX provided better predictions of the peak pressures recorded on the Phase 3 tests than did SHARC, it was also evaluated as an airblast hazard prediction tool for underground magazines (Reference 15).

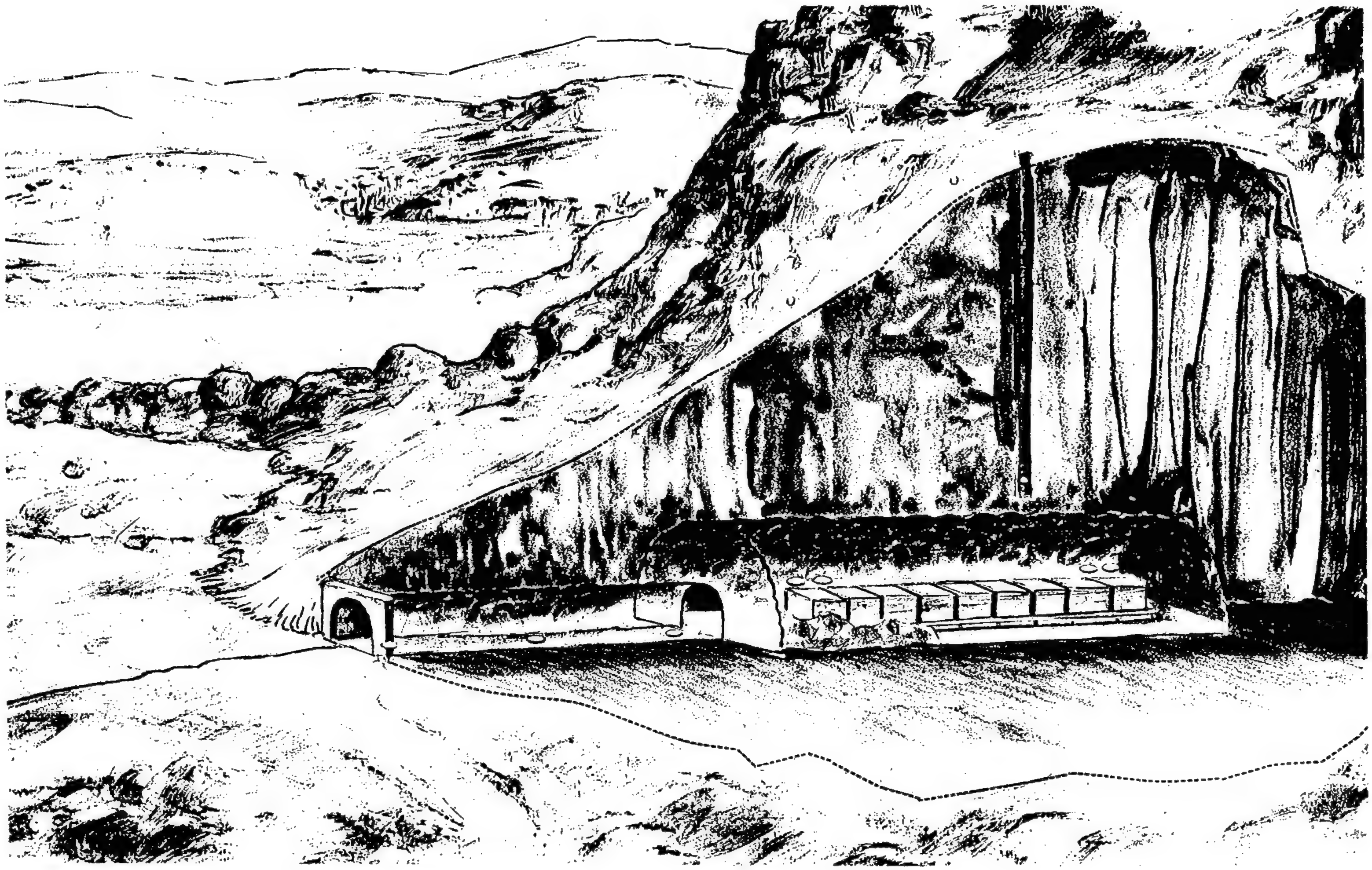


Figure 2.1 Half-scale, shallow "shotgun"-type underground magazine constructed for Klotz Club-sponsored explosion hazard test at China Lake, CA in 1988.

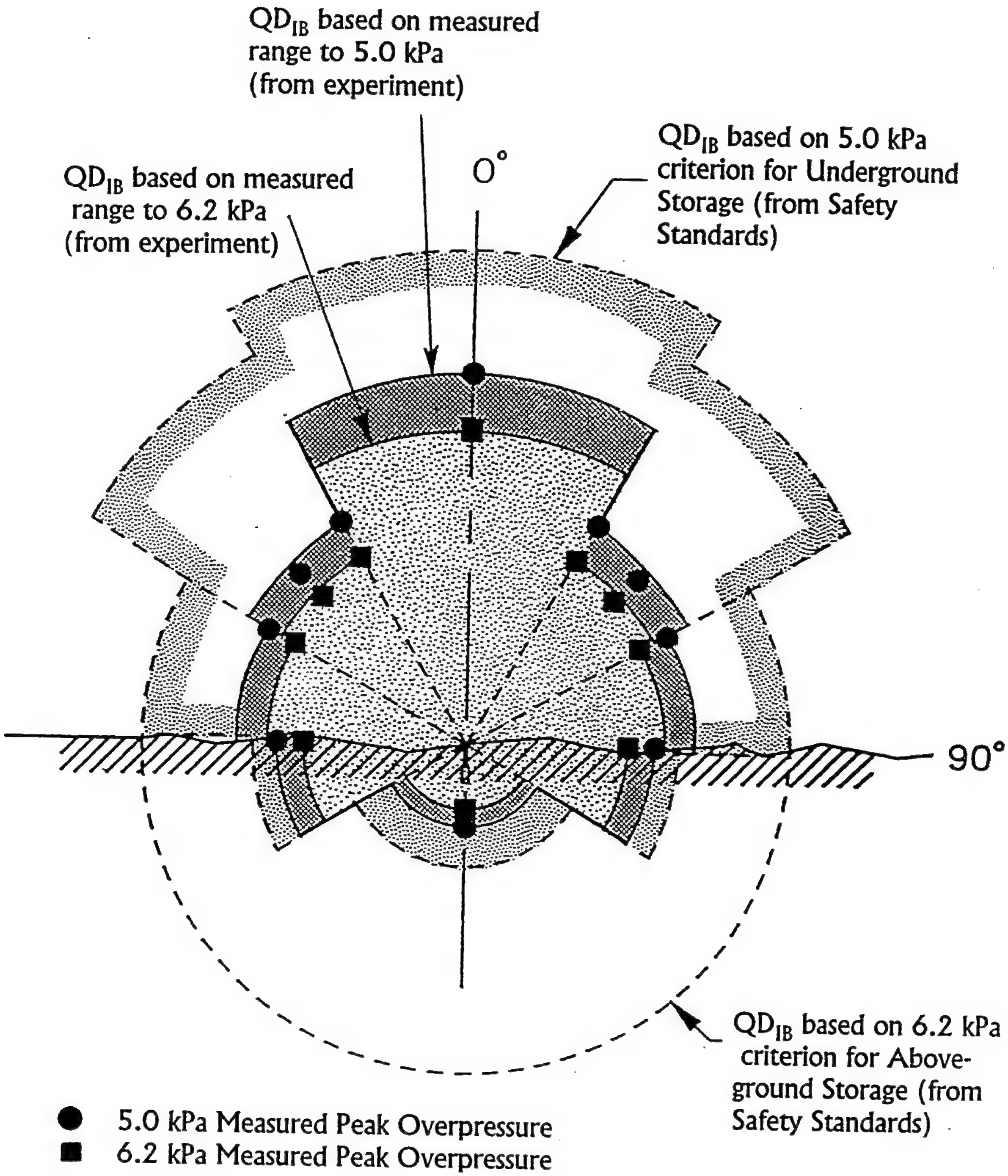


Figure 2.2 QD area defined by 1988 Klotz Club test, compared to QD area specified by existing U.S. DoD safety standards.

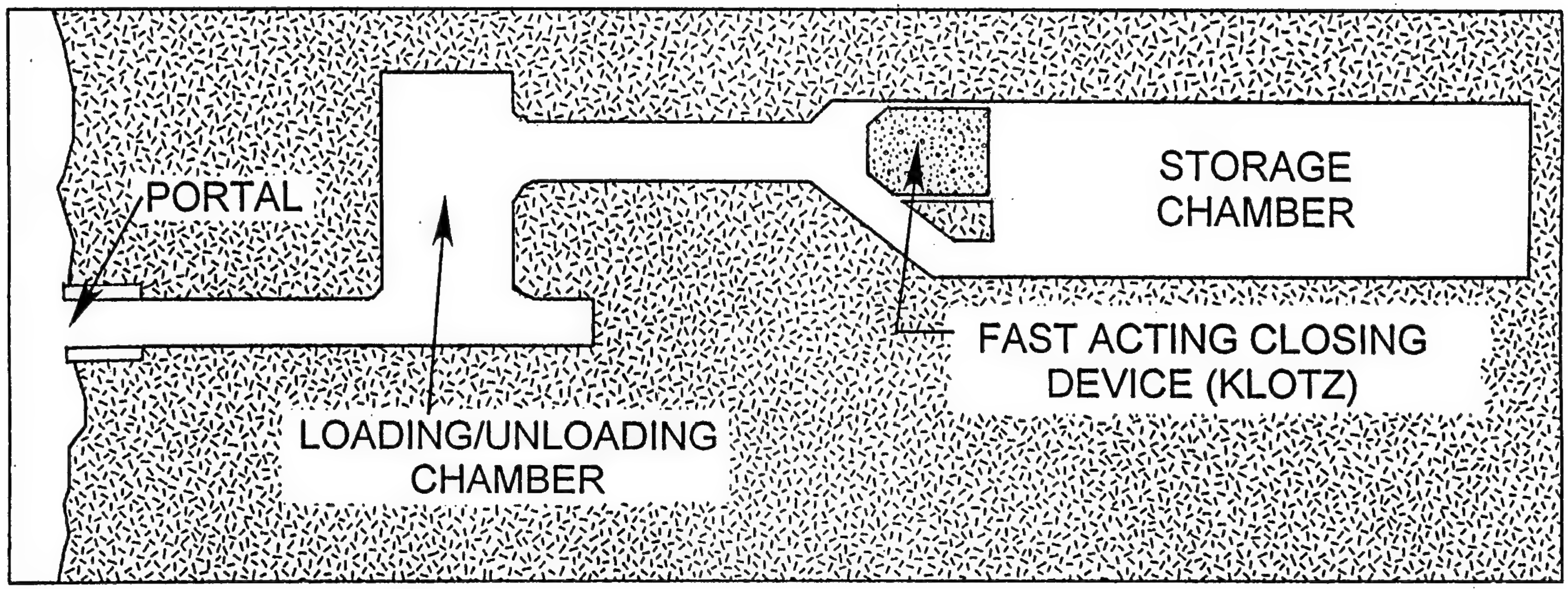


Figure 2.3 The Klotz Block; an explosion-driven, chamber closure device developed in Switzerland around 1971 and tested by the Klotz Club in Sweden in 1989.

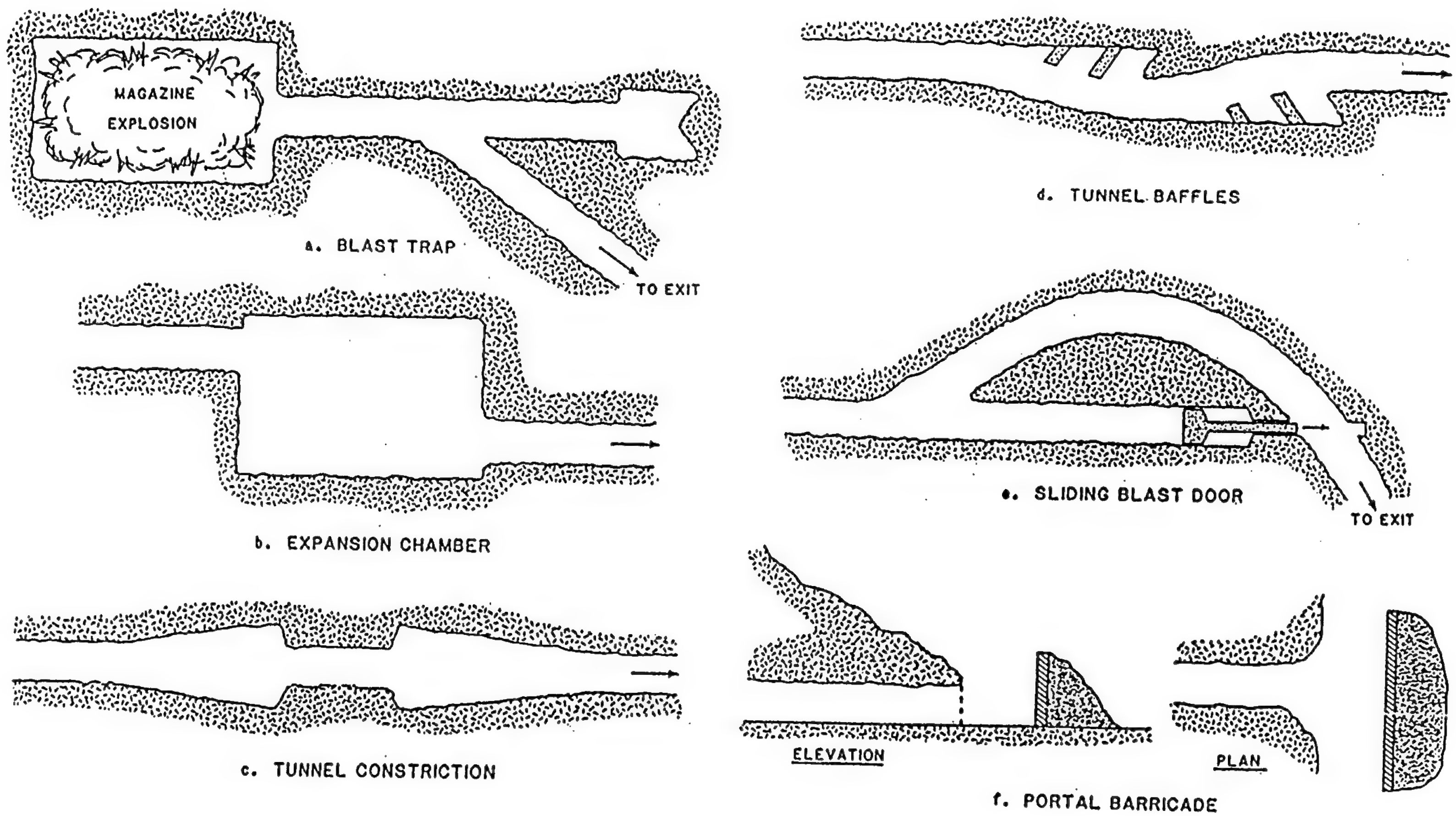


Figure 2.4. Blast and debris control features originally proposed for investigation in UAST program.

PART 3

SUMMARY OF ACTIVITIES

3.1 PHASE 1: R&D PREPARATION AND PLANNING

3.1.1 Purpose.

Due to the scope of research required for the entire UAST program, a significant effort was made in Phase 1 to plan the division of work between the U.S. and the ROK, organize research teams, acquire appropriate test equipment and state-of-the-art computer programs, construct model magazines for the Phase 2 program of small-scale tests, and develop detailed plans for the small-scale experiments. The following sections describe specific Phase 1 activities in the ROK and the U.S.

3.1.2 The ROK Program.

Reference 16 provides details of the ROK activities in Phase 1, which are summarized below:

a. **Organization of Research Teams**. Four research teams were organized under the direction of the ROK Technical Project Manager: the Design and Evaluation Team, the Blast Wave Theory Team, the Numerical Modeling Team, and the Test and Measurement Team.

b. **Preparations for Tests**. A number of test equipment items and analysis tools were purchased, such as piezo-electric and piezo-resistive gauges, signal conditioning amplifiers for airblast measurements, a programmable multi-channel digitizer, accelerometers for ground shock measurements, and an engineering work station for numerical simulations. An ADD electronics engineer traveled to WES for training in the experimental techniques of blast measurement and analysis for a month.

c. **Small-Scale Tests and Results Analysis**. Two blast pressure measurement tests were made using a 1/30-scale steel model magazine. The objective was to check the applicability

of the existing blast pressure measurement technique to the chamber/tunnel system and the free field. Signals from most gages were successfully recorded, which suggested that the technique was applicable for the model tests of interest (Reference 17).

d. **Computer Simulation of Small-Scale Tests**. An ADD computer scientist traveled to WES for a month of training in techniques for computer simulation of explosions in underground storage. Computer simulations of small-scale tests were made and their results were compared with ADD's experimental results. The effect of configurations of blast traps on blast wave propagation was also simulated.

e. **Design of Small-Scale Model Magazine and Test Plan for Phase 2**. A small-scale steel model magazine, which could be used repeatedly, and concrete model magazines, which would be broken as they were tested, were designed. A test plan was established for small-scale tests with magazines in Phase 2.

f. **Supporting Research**. A contract research study, titled "Design Factors for Underground Ammunition Storage Site and Evaluation of Current Above-Ground Facilities," was conducted by LTC Kim Oon-Young of the Korea Military Academy, from July 1991 to April 1992 (Reference 18). The following is an abstract of this research:

> "The design factors for ammunition storage facilities can be divided into three categories, which are the explosion safety, construction, and operation features. Since the safety criteria places limits on the chamber separation intervals, access and main passageways, intersections of tunnels, etc., the layout of an underground site should be determined on the basis of the above factors, as well as conventional tunnel design factors, such as the geological conditions. Therefore close cooperation between the military authority, which is responsible for ammunition storage/control, and the geologists and engineers is strongly recommended.

The current safety criteria is based on the shotgun type of single-chamber magazine, and blast protection measures--blast doors, closure blocks, multiple entrances, etc.-- are not taken into account. To achieve both design goals (minimization of explosion effects and maximization of storage capacity), more R&D is still needed.

In addition to R&D for standard underground magazine designs, an investigation of the planned magazine site is recommended with respect to the geological and geographical conditions. Also, measurements of the temperature and humidity in the tunnels of the planned underground storage test facility will provide valuable information for future design development."

3.1.3 The U.S. Program.

a. Establishment of Technical Advisory Group. To help guide the U.S. portion of the UAST study, a Technical Advisory Group (TAG) was established, consisting of experts in the areas of explosives safety, explosion effects, engineering design, and ammunition logistics. The TAG membership was drawn from all three U.S. services (Army, Navy, and Air Force) to ensure that the ammunition storage requirements of all three were represented, and that the results of previous or on-going R&D efforts by all the three services were available to support the program.

The TAG met at least twice each year through the life of the program, to review and comment on R&D results and plans. The chairman of the TAG was Dr. Chester Canada of the U.S. DOD Explosives Safety Board Secretariat. Members were:

(Successively) Mr. Robert Fahy Mr. Raymond Freeman	Office of Deputy Chief of Staff for Ammunition U.S. Army Material Command Washington, DC
(Successively) Mr. Marc G. Davis Mrs. Barbara Overton Mr. Lou Bournstein	Munitions Division (J-4) U.S. Forces/Korea Seoul, Korea

Mr. Bill Gaube	Missouri River Division/Omaha District U.S. Army Corps of Engineers Omaha, NB
Mr. Paul LaHoud	Huntsville Division U.S. Army Corps of Engineers Huntsville, AL
(Successively) Mr. Ona Lyman Mr. John Starkenburg	U.S. Army Research Laboratory Aberdeen Proving Ground, MD
Mr. Paul Price	U.S. Air Force Safety Agency Kirtland AFB, NM
Mr. Michael Swisdak	U.S. Naval Surface Warfare Center Silver Spring, MD
Mr. James Tancreto	U.S. Navy Facilities Engineering Services Center Port Hueneme, CA

b. Preparation for Small-Scale Experiments. Gages, cables, and other materials were acquired in preparation for the small-scale test program planned for Phase 2. A blast chamber and sections of steel pipe were fabricated to construct the model, and a detailed program of tests was developed.

c. Computer Model Studies. The SHARC hydrocode was used by WES (Reference 19) in a study of the effect of expansion chamber length and diameter on airblast passing through a tunnel (see Figures 3.1 and 3.2). Other calculations were made to examine the effect of the other parameters, such as the ratio of the tunnel diameter to the storage chamber diameter (Reference 20).

d. Supporting Studies. Over 100 reports and technical papers dealing with various aspects related to the explosives safety problem for underground magazines were gathered and reviewed. The results were used to summarize the "state-of-the-art" for designing and

constructing underground magazines, and for predicting and controlling the hazardous effects of accidental explosions of the stored ammunition (Reference 13).

A study was performed (Reference 5) to determine if airblast data from small-scale tests of shallow, "responding" magazines (where the explosion ruptures the chamber cover) could be assumed to provide realistic "scaled" results. The analysis showed that the results of tests with responding models was of questionable value, due to the inability to scale the inertia of the rock cover. The disproportionally greater inertia of full-scale magazine covers would result in longer confinements of chamber pressures, which could, in some situations, produce greater airblast QD's from the portal. It was concluded, however, that as long as the storage chamber remains intact (non-responding model), then airblast data from small-scale tests should be valid.

3.2 PHASE 2: SMALL-SCALE TEST PROGRAM

3.2.1 Purpose.

The U.S. and ROK small-scale tests conducted in Phase 2 were mainly designed to investigate airblast phenomena. The analysis of previous research showed that airblast in confined areas, such as underground tunnels and chambers, has two components--the initial air shock front, including secondary reflections, and the gas pressures created by the detonation products. Many of the previous tests were performed in shock tubes to investigate the propagation of a shock wave in tunnel systems with bends and intersections. Later tests by the U.S. Army Research Laboratory, and tests conducted by Switzerland and Norway, used higher explosive densities, but were performed at very small scales (e.g., 1:100 and 1:50).

The small-scale tests conducted in Phase 2 of the UAST program were designed to provide more extensive and reliable measurements of the shock and gas pressure propagation. The basic objective of Phase 2 was to use this data to evaluate the effectiveness of different design features in underground magazines for reducing the external airblast levels from explosions in the magazine storage chambers.

Additional objectives were to:

- o Develop an understanding of the basic physics of airblast production and propagation in confined environments.
- o Perform a set of carefully-controlled, physical model tests that could be used to evaluate the airblast prediction accuracy of numerical computer models.
- o Develop a small-scale test data base that, together with data from previous large-scale tests and the intermediate-scale tests to be conducted in Phase 3, could be used to investigate scaling relationships for the various phenomena of interest.
- o Provide a basis for designing the Phase 3 intermediate-scale tests, based on a "down-selection" of the magazine design features that were effective in reducing external blast.

3.2.2 Division of Research.

In general, the small-scale tests conducted by the ROK involved chamber loading densities that were relatively high (up to 40 kg/m^3) in 1:30-scale model magazines. Most of the U.S. small-scale tests, on the other hand, had lower loading densities (up to 5 kg/m^3), but used a larger test scale of 1:20.

There were several design features that were tested by both sides to ensure commonality between the ROK and U.S. test programs. These included items such as variations in chamber loading densities and the effects of tunnel blast traps. For the most part, however, the U.S. and ROK small-scale test programs concentrated on separate features of underground magazine designs.

The main thrust of the ROK program was to evaluate the effects of tunnel constrictions and the different concepts for sealing chambers to contain the high blast pressures. The main thrust of the U.S. program was to examine the effects of different types of tunnel intersections

and complex tunnel layouts (including multiple exits, expansion chambers, rough-walled tunnels, etc.), and potential hazard control features such as water mitigation of blast effects from chamber detonations, external trench-type barricades, etc.

Reference 21 provides a comprehensive descripton of the research efforts and results of Phase 2 of the UAST program. Additional details are given in specific reports listed in the References or as "Additional UAST Reports."

3.2.3 ROK Phase 2 Program.

a. Tests at Low Loading Densities and Analysis of Results.

(1) Procedures. A 1/30-scale steel model magazine, which could be used repeatedly, was manufactured, and tests were performed. The model storage chamber was 100 cm long, 50 cm wide, and 23 cm high. Steel pipes of 19.2-cm inside diameter and 1.27-cm thickness were used to form the tunnel. In all tests, the same storage chamber was used, but the configuration of the tunnel was changed depending on the nature of the test. This chamber/ tunnel system was used for tests with chamber loading densities less than 16.5 kg/m^3.

In order to evaluate the blast-reducing effect of various design features, side-on airblast pressures were measured inside and outside of the model magazine. The tunnel pressure was measured using gages installed on the inner surface of the tunnel pipes. Free-field pressures were measured along the extended tunnel axis (0° azimuth) and along the 30, 60, and 90-degree azimuth angles from the tunnel portal. Composition C-4 was used as the test explosive in all tests. The weight of the charges was varied, but 1.9 kg was used for most tests.

Peak tunnel pressure data for each chamber/tunnel configuration was plotted as a function of explosive weight/total volume (Q/V_t), and compared with the portal pressure prediction equation in the current U.S. explosives safety standards (Reference 1),

$$P_w = 1{,}770\ (Q/V_t)^{0.45} \tag{3-1}$$

where P_w is the portal pressure (in kPa), Q is the explosive weight (in kg), and V_t is the total volume (in m^3) from the point of explosion to the gage location, assuming that the blast wave moves at a constant speed regardless of the cross-sectional area of the tunnel.

Peak free-field pressure for each chamber/tunnel configuration was fitted to the equation,

$$P_w/P = a_w(R/D)^{1.35} \tag{3-2}$$

where P is the blast pressure at a location of interest, a is the fitting coefficient, R is the distance (in meters) from the tunnel portal to the location of interest, and D is the tunnel diameter (in meters). The value of the coefficient, a_w, was compared with the value implied in the DoD equation ($a_w = 1.0$).

A relative pressure ratio, *RPR*, was used to compare the measured pressure, for a given test situation, to the pressure predicted by the DoD equation. The value of *RPR* is simply the ratio of the coefficients,

$$RPR = 1/a_w \tag{3-3}$$

Accordingly, the relative IBD ratio, R_{IBD}, is

$$R_{IBD} = (1/a)_w^{1/1.35} = a_w^{-1/1.35} \tag{3-4}$$

The relative hazard area, *RHA*, then is expressed by

$$RHA = (R_{IBD})^2 = a_w^{-2/1.35} = a_w^{-1.5} \tag{3-5}$$

The blast-reducing effect of each chamber/tunnel configuration was evaluated by comparing the value of *RHA* to a prediction from the current DoD equation.

(2) Shotgun-Type Magazines. The shotgun-type magazine was selected as the standard baseline in evaluating the blast-reducing effect of different chamber/tunnel configurations. Six tests were conducted using this magazine. In these tests, characteristics of piezo-electric type

gages and piezo-resistive type gages were compared, and the effect of explosive weight (i.e., loading density) was also evaluated.

The measured tunnel pressures were slightly higher than predicted by the DoD equation. This was apparently because the surface of the storage chamber and the tunnel in the test magazine was smooth, which reduced the attenuation of the blast pressure. When the free-field pressure was fitted to Eq. (3-2), the value of the coefficient a_w was determined to be 0.96, which agrees well with the value of 1.0 in the DoD equation.

(3) Length of Blast Traps. To investigate the effect of blast-trap length, ten tests were conducted; four without blast traps, and two each with trap lengths equivalent to one, two, and three tunnel diameters. From the measured pressures, the value of the coefficient a_w ranged from 1.11 to 1.27 for all blast trap configurations. The relative hazard area ratio, *RHA*, ranged from 0.78 to 0.86 for trap lengths varying from zero to three tunnel diameters, which suggested that the effect of blast trap length on airblast peak pressure reduction was not great.

(4) Location of Blast Traps. To determine the effect of blast-trap location on blast reduction, eight tests were made; two tests each for blast trap locations near the chamber, at the middle of the tunnel, near the portal, and with dual blast traps (two locations). The coefficient a_w and the relative hazard area ratio, *RHA*, varied from 0.85 to 0.96 and from 0.78 to 0.94, respectively. These test results showed that the effect of the blast trap location was not great. Even with dual traps, the effect was not significant.

(5) Loading/Unloading Area. To evaluate the effect of a loading/unloading area (or an expansion chamber), four tests were conducted; two tests of an expansion chamber with a single exit, and two tests with dual exits (blast pressure was measured in both exits). The exit near the storage chamber was in a direction normal to the axis of the tunnel and expansion chamber, and the exit far from the chamber was parallel to the chamber axis. The tunnel pressure for the configuration with double exits was lower than for one with a single exit. The pressure for both configurations was sharply decreased after the blast wave passed through the loading/unloading

area. The pressure near the portal was considerably lower than that predicted by the current DoD equation. The coefficient a_w and the relative hazard area ratio, *RHA*, were determined to be 0.83 to 1.10, and 0.87 to 1.32, respectively. The values of a_w and *RHA* for the single-exit case were higher than those predicted by the current safety standards. For the dual-exit case, the portal pressure at the far exit was higher than that at the near exit. This was because the blast wave entering the loading/unloading area continued directly toward the far exit, rather than turning to the near exit.

b. Tests at High Loading Densities. Fourteen small-scale concrete magazines were constructed and tested. The storage chamber volume in the concrete magazines was the same as that of the steel magazines. The same steel tunnel was used. The pressure in the tunnel and in the free-field was measured and analyzed by the same method as that used in the steel magazine tests. The concrete magazines were used for tests where (1) the shape of storage chamber was changed, (2) the shape of the closure block was changed, or (3) the chamber loading density was so high that the test was not feasible with the steel chamber.

(1) Blast-driven Closure of Parallel-Type Chambers. In the parallel-type chamber, the axis of the storage chamber was parallel to the chamber access tunnel. The entrance into the chamber was designed to be sealed when the explosion blast pressures drive a free-standing closure block against the opening of the chamber access tunnel (see Figure 3.3a). The closure blocks were made by pouring concrete into a mold constructed of 3 mm-thick steel plates. Four tests were made with three different designs of parallel-type chambers. By analyzing the measured free-field pressures, the pressure coefficient a_w and the relative hazard area, *RHA*, were found to range from 1.80 to 2.49 and from 0.16 to 0.42, respectively. The *RHA* value of 0.42 was obtained in the test with a chamber loading density of 20 kg/m^3, which was half that of the other tests. From these results, the blast-reducing effect of the closure blocks was found to decrease with decreasing chamber loading density. Figure 3.3b illustrates the hazard area reduction achieved with an *RHA* value of 0.16.

(2) Blast-driven Closure of Perpendicular-Type Chambers. In the perpendicular-type of storage chambers, the long axis of the chamber was perpendicular to the chamber access tunnel. The closure block was made by the same method as in the parallel-type chamber tests. Five tests were made with four different types of closure blocks. By analyzing the test results, the pressure coefficient a_w and the relative hazard area, *RHA*, were evaluated to be from 1.38 to 3.37 and from 0.15 to 0.61, respectively. The *RHA* value of 0.61 was obtained in the test with a chamber loading density of 20 kg/m^3. For chamber loading densities over 40 kg/m^3, the *RHA* value was in the range of 0.15 to 0.31, which indicated that a 70 percent (or more) reduction in hazard area might be obtained by using the perpendicular-type chambers.

The motion of a closure block is dependent on the weight and cross-sectional area of the block, and the blast pressure acting on the area of the block faces. The pressure acting on the block, P_b, can be approximated by Eq. (3-1). The force acting on the block, *F*, is given by

$$F = m_b \, a_b = P_b \, A \tag{3-6}$$

where m_b is the mass of the block, a_b the acceleration of the block, and *A* the cross-sectional area of the block. From Eqs. (3-1) and (3-6), the acceleration is:

$$a_b = \frac{1{,}770 \, (Q/V_t)^{0.45}}{m_b/A} \tag{3-7}$$

From the test results, the relative hazard area, *RHA*, was defined as a function of the acceleration, a_b, as

$$RHA = \exp[(-0.00007 \, a_b)] \tag{3-8}$$

(3) Dual Closure Block Chamber. In chambers with dual closure blocks, the long axis of the chamber was parallel with to the chamber access tunnel. Two different types of chambers were tested; one for closure blocks where the block was free-standing (separated from the wall of a chamber), and one for wall-type closures, where sections of the chamber wall itself were designed to be blown into the access tunnel by the explosion. The pressure coefficient a_w and the

relative hazard area, *RHA*, were determined to be 1.29 and 0.86 for the block type, and 2.22 and 0.31 for the wall type, respectively. Contrary to expectations, the wall type had a better blast-reducing effect than the block type.

(4) Chamber Aspect Ratio. In the magazine to test the effect of the aspect (length-to-diameter) ratio of a chamber, the chamber opening was on the long side. From the single test that was conducted, the coefficient a_w and the relative hazard area, *RHA*, were determined to be 0.92 and 1.33, respectively. For this type of magazine, the tunnel pressure was lower, but the free-field pressure was similar to those of the shotgun-type magazine, which suggested that an increased aspect ratio magazine is not effective in reducing blast.

(5) Loading/Unloading Area (Expansion Chamber). For the magazine with a loading/unloading area, between the storage chamber and the tunnel portal, the pressure coefficient a_w and the relative hazard, *RHA*, were determined to be 18.87 and 0.01, respectively. These values of a_w and *RHA* were much lower than expected. By reviewing a video tape of the test, it was found that flame was thrown out from the entrance portal and through the earth cover at the same time, which was completely different from observations in other tests. That is, a considerable part of the blast escaped through the rupture of the chamber cover. This explained why the measured free-field pressure outside the tunnel portal was significantly lower than expected. The fact that this result is the opposite of that from the 1/2-scale 1988 Klotz club test at China Lake, CA (Reference 4), supports the finding of Reference 5 that airblast from "responding"magazines cannot be correctly modeled in small-scale tests (see Section 3.1.3d).

c. **Numercial Simulation of Blast Propagation in Small-Scale Magazines**. In an attempt to identify and explain the discrepancies in results between SHARC and HULL code calculations, the blast propagation from a 1-kg bare TNT charge explosion was simulated in a two-dimensional (2-D) grid, using the same Equations of State for the explosive and air in both codes. The pressures calculated by the SHARC code were considerably higher than those calculated by the HULL code. Since the same grids and Equations of State were used, it was

concluded that the differences in the calculated results were caused mainly by inherent differences in the codes themselves.

To justify making 2-D calculations for 3-D models, an explosion in a very simple shotgun type magazine (unlike the more complex design of the previous calculations) was simulated by using both the SHARC and the HULL code in 2-D and 3-D. The 2-D calculations give higher pressures than the 3-D calculations. Surprisingly, the results calculated by both codes were almost the same, which was completely different from all other calculations. It was speculated that both codes might produce the same results for very simple modeling configurations.

Small-scale tests with a blast trap, the length of which was varied from 0 to 60 cm, that were performed by ADD were simulated in 2-D calculations. To investigate the effect of the 2-D conversion, one test was modeled in both 2-D and 3-D. Three different calculations were made using different mesh sizes for the same test. From these calculations, the unit height of the 2-D conversion was set to 20 cm and the mesh size 2×2 cm. The free-field blast pressure calculated by the SHARC code was generally higher, except at a few points, than that calculated by the HULL code. In the HULL code calculations, the longer the blast trap, the lower was the pressure.

d. Planning for Intermediate-scale Tests. An area in a military camp located in Yeonchun-gun, Kyungki-do was selected as the site for the ROK intermediate-scale tests. A land survey to lay out the test area was completed.

Based on results of the small-scale tests, the closure block was selected as a device to be investigated thoroughly in the intermediate-scale tests. It was planned to construct blast traps at positions in the tunnels facing the storage chambers, in order to intercept debris transported by the blast. Based on results of the literature survey, it was planned to include tunnel constrictions, an expansion chamber, and a concave external barricade in the tests.

e. Supporting Research. A contract research study, titled "Analysis Method for Structural Safety in the Design of Underground Ammunition Storage Facilities," was conducted by LTC Kim Oon-Young of the Korea Military Academy and Professor Lee Sang-Duck of Ajoo University, from April 1992 to March 1993 (Reference 22). The following is an abstract of the study:

> "The analysis method and its computation results on the structural safety problem of underground ammunition storage facilities are described based on the Mohr-Coulomb Elastic-Plastic Theory and the Finite Difference Method.
>
> There is no indication of structural failure if the underground ammunition storage facilities are built in sound rock under the present design concept, but several facts with respect to the deformation characteristics of underground chambers must be considered. First, heaving displacement of the chamber floor can be as large as settlement displacement of the ceiling, when the ratio of the chamber width to height is large. Therefore rock reinforcement, such as a rockbolt system, is desired in areas where large heaving is expected.
>
> The separation distance between chambers as determined by explosive safety criteria should be enough for structural safety. Finally, the slope of the mountain outside the underground facility can have a pronounced effect on the deformation behavior of an underground chamber. Therefore, a global safety evaluation should be performed first before performing a local analysis of each tunnel section."

3.2.4 U.S. Phase 2 Program.

The general objective of the small-scale test program conducted by the U.S. was to investigate and quantify the influence of different design features of the tunnel/chamber system on the blast wave, as it travels from the detonation source in the storage chamber to the area outside the tunnel entrance portal. The effect of some of these features, such as expansion chambers, constrictions, tunnel wall roughness, etc., was known in a general sense from the previous

research evaluated in the Phase 1 Literature Analysis (Reference 13). It was important, however, to develop more reliable, extensive, and specific data for such features, as well as to evaluate other features for which no previous information existed. Furthermore, it was essential to relate these effects to a common experimental base, in terms of test scales, explosive sources, model design and construction, measurement techniques, etc. Finally, it was also important to acquire such test data in a manner that was comprehensive and detailed enough to both understand the "physics" of the phenomena under study, and to develop fundamental relations that could be applied to a broader range of future problems.

The specific objectives of the U.S. small-scale test program were to evaluate the following tunnel/chamber design features:

- Chamber loading density
- Tunnel/chamber diameter ratio
- Access tunnel length
- Tunnel bends
- 90° and 45° "T" intersections
- 90° and 45° side intersections
- Blast/debris traps
- Chambers with two (opposed) exits
- Constriction at chamber entrance
- Tunnel wall roughness
- Expansion chambers
- Pressures in adjacent (unsealed) chambers
- External trench barricades
- Water tamping of detonations

a. Baseline Magazine Design. It was necessary to begin the small-scale experiments using a baseline or "control" tunnel and chamber design. The baseline selected was the simple "shotgun" magazine shown in Figure 3.4. This basic was the same design tested in the 1/2-scale, shallow-buried magazine experiment conducted for the Klotz Club at China Lake, CA in 1988 (Reference 4). The blast mitigation effects of all the design features tested in the U.S. small-scale tests were evaluated by comparison with the blast pressures from this baseline design.

The primary model scale used in the U.S. small-scale test program was 1:20, assuming a full-scale underground chamber 15 m wide, 7 m high, and 30 m long, with a volume of 3,000 m^3.

b. Test Procedures. The U.S. small-scale tests used a cylindrical steel blast chamber to model the magazine storage chamber, and sections of steel pipe to model the access tunnels. The blast chamber had an internal diameter of 50 cm, a wall thickness of 15 cm, and a length (internal) of 1.8 m (see Figure 3.4). The tunnels were constructed of sections of heavy-wall steel pipes 1.0 m in length, with internal diameters of 14.6, 24.3, or 36.4 cm. Circular steel plates 7.6 cm thick were bolted to the front and rear ends of the blast chamber. The rear plate was removed and replaced for loading the explosive charges.

Because of its ready availability, its well-documented detonation characteristics, and its history of good performance in past small-scale explosive tests, Composition C-4 was selected as the explosive for the U.S. small-scale test program.

Kulite Model HKS and XT-190 piezoelectric pressure gages were used to measure overpressure time-histories in the detonation chamber, in the connecting tunnels, and on the ground surface outside the tunnel portal. For the tunnel and chamber measurements, the gages were mounted in holes drilled through the pipe and chamber walls, and tapped so that the gages could be screwed into place with the head of the gages flush with the inside tunnel or chamber surface. External gages were mounted flush with the ground surface in concrete gage mounts (30 cm in diameter and 10 cm deep).

c. Results. The following sections summarize the results of the U.S. Phase 2 tests. The effectiveness of each blast reduction feature was described in terms of the airblast Quantity-Distance for inhabited buildings, QD_{IB} , beyond the tunnel portal, using the current DoD criterion of 6.2 kPa of peak airblast pressure (Reference 1).

The effect of loading density was defined in the tests of the two baseline magazines; Control Design A, with a tunnel/chamber diameter ratio of 0.3, and Control Design B, with a ratio of 0.5. All other design features were evaluated by comparing their QD_{IB} values to those of the control designs, for the same loading densities.

(1) Loading Density. In the tests with the baseline magazine design, the chamber loading density was varied from 1.67 to 5.0 kg/m^3 (0.61 to 1.83 kg in actual explosive weight). The charge geometry was kept constant; i.e., a cylindrical charge along the central axis of the chamber, detonated at the rear end. The 5.0 kg/m^3 loading density was used as the standard charge weight for the remainder of the small-scale test program. The test results showed clearly that, as predicted by the conventional scaling law for explosion effects, the peak airblast pressure varied as the cube root of the explosive weight. Since the total volume of the test magazine did not change, this confirmed that the peak pressure for an underground magazine varies as the cube root of the loading density. This relation held consistently true through the remaining program of small-scale tests.

Twenty-seven tests were conducted with the two "shotgun" magazine models. Using the current DoD criterion of 6.2 kPa of peak airblast overpressure, the Control Design A tests at 5 kg/m^3 had an average QD_{IB} of 20.8 m. For Control Design B, the average QB_{IB} was 29.2 m.

(2) Tunnel/Chamber Diameter Ratio. With the 50 cm-diameter chamber, tunnel/chamber diameter ratios of 0.3 to 0.73 were tested, all with one, two, and four-meter tunnel lengths. Using the Control Design A (0.3 tunnel/chamber diameter ratio) as a base, an increase in the ratio to 0.5 increased the average QD's by 32%. A further increase in tunnel diameter to a ratio of 0.7 increased the average QD's by only 22% above the Control "A" tunnel, however.

Figure 3.5 is a plot of the QD values as a function of the *total* loading density (i.e., the storage chamber volume plus the tunnel volume) for Control A and Control B tests. The two control groups clearly fall into two separate data bands. Also shown in this figure are data from previous studies involving tests of "shotgun" magazine designs with similar tunnel and chamber geometries. The key data point is that representing the half-scale (20,000-kg charge weight) 1988 Klotz Club test, fired in a rock chamber, with a tunnel/chamber diameter ratio of 0.5. Also shown are data from the 1:75-scale tests conducted by WES in 1980 (Reference 23). While the 1:75-scale data at low loading densities fall below the other data, the 1:75 tests at higher loading

densities and the 1988 Klotz Club test compare very well with the results of the Control A and B series.

(3) Tunnel Length. Model tunnel lengths of one, two, and four meters were tested, with the variations in loading density and tunnel diameter as mentioned in the previous sections. Theoretically, the peak external pressures should decrease in about the same proportion that the total magazine volume is increased by increasing the tunnel length. However, most of the 27 tests showed only a small reduction in external pressures (10 percent or less). This was true even for the large tunnel, which increased the total volume by about 66 percent when the tunnel length was increased from one to four meters.

(4) Tunnel Bends. Tests were performed with 4 m-long, 14.6 cm-diameter tunnels containing 90-degree bends at different distances from the chamber and near the portal. For a bend location 1 m from the chamber, the QD_{IB} was reduced an average of 21%, compared to the straight tunnel of Control Design A. For a bend located at two meters, the reduction averaged over 28%. When the bend was located near the portal, however, the results were somewhat inconsistent, with much lower reductions.

(5) Tunnel Intersections. Figure 3.4 shows a typical model tunnel layout with a 90° "T" intersection in the exit tunnel. For nine tests at loading densities of 1.07 to 5.0 kg/m^3, the measured QD's averaged 38 percent less than that for the Control B "shotgun" design.

For a "T" intersection where the two arms of the T are at 45° and 135° angles to the tunnel extending from the chamber (the stem of the T), the QD reductions for the downstream (135°) arm ranged from 10 to 22 percent, with an average of 16 percent. For the upstream (45°) arm, the reductions ranged from 28 to 42 percent, with an average of 34 percent.

Tests were also performed to evaluate the effect of blast traps of different lengths at tunnel intersections. For both the 90° and the 45°/135° "T" intersections, the blast traps actually seemed

to have a negative effect. Where some reduction in QD was obtained without the blast traps (due to the intersection), the same tests with blast traps showed little or no reduction in QD.

Figure 3.6 shows the QD_{IB} values measured on tests of magazines with "T" intersections, compared to the baseline values for Control Design B.

(6) Chambers With Two (Opposed) Exits. Seven tests were preformed to investigate the effect on external airblast of having two exit tunnels from the storage chamber, rather than one exit tunnel as normally used. For these tests, a steel "sleeve" was inserted into the normal blast chamber. The sleeve reduced the chamber diameter to 14.6 cm, but allowed tests over a greater range of chamber loading densities; from 1.0 to 42.0 kg/m^3. This reduced the model scale to 1:40, compared to 1:20 for the previous tests. Therefore, to compare these test results to the previous data, the 1:40-scale QD values were multiplied by 2.0. The second exit extended from the rear of the test chamber, along the same axis but in the opposite direction from the main exit. The test results indicated that the presence of the second exit from the storage chamber provides no reduction in QD (from either tunnel portal) compared to having only a single exit.

(7) Tunnel Wall Roughness. The test arrangement described above for the two-exit tunnel tests was also used to investigate the effect of tunnel wall roughness on external airblast. The rough-walled sections were made by milling V-shaped grooves up to 5.6 mm deep around the inside of the pipe leading from one of the chamber exits. This provided roughness factors (as defined in Reference 9) of up to 8 percent for the tunnel walls. The pipe from the opposite chamber exit was left smooth. Tests were conducted at loading densities of 1.0 to 15.0 kg/m^3. The results showed that the rough-walled model tunnels reduced the QD's of smooth-walled tunnels by 15 to 20 percent.

(8) Expansion Chambers. Two general types of expansion chambers were tested; those whose central axis was aligned parallel to the axis of the access tunnel, and those whose central axis was normal to that of the access tunnel. Chamber loading densities of 1.7 to 5.0 kg/m^3 were used.

The "in-line" expansion chambers (aligned with the tunnels) had diameters ranging from 2.6 to 4.0 times the 14.6-cm tunnel diameter, and were approximately 14 tunnel diameters in length. When located near the portal, the in-line expansion chambers consistently produced QD reductions of 60 to 80 percent. When the expansion chambers were located nearer to the storage chamber, the reductions were somewhat less--in the range of 40 to 60 percent.

Figure 3.7 shows a typical layout for tests of expansion chambers positioned transverse to the axis of the exit tunnel. Several different configurations were investigated--with one forward exit tunnel (offset from the main tunnel axis), with two offset forward exit tunnels, and with one offset exit tunnel extending in the reverse direction from the expansion chamber. Surprisingly, the transverse expansion chambers did not contribute any benefit beyond the effect of the larger total volume of the model.

(9) <u>Blast Pressures in Adjacent Chambers</u>. Three tests, with chamber loading densities up to 5.0 kg/m^3, were performed to record blast pressures produced in a second chamber adjacent and parallel to the detonated storage chamber. Both chambers had 14.6 cm-diameter access tunnels connecting to a common main tunnel of the same diameter. The peak pressures recorded in the "acceptor" chamber were 80 to 90 percent less than the pressures in the detonation chamber, and about 60 to 65 percent less than the pressures in the main tunnel (at the entrance to the acceptor access tunnel).

Additional tests were made with the adjacent chamber being perpendicular to the axis of the main chamber and its "shotgun"-type access tunnel. Based on all seven tests (three with parallel and four with perpendicular adjacent chambers), the peak pressures in the adjacent chamber were consistently about 85 percent less than those in the detonated storage chamber.

(10) <u>Constriction at the Chamber Entrance</u>. Five tests were performed with the shotgun magazine design to investigate the effect of a tunnel constriction at the entrance to the storage chamber. The constriction was formed by inserting a circular steel plate behind the front wall of the chamber, with a 4.6 cm-diameter hole in the plate centered on the tunnel/chamber axis. The

hole in the plate (i.e., the constriction) had a diameter approximately one-third that of the tunnel. Tests were conducted with 1.7 to 5.0 kg/m^3 loading densities. The constriction reduced the QD values by 54 to 73 percent, with an average reduction of 63 percent. The greater reduction occurred at the 5.0 kg/m^3 loading density, implying that constrictions may be more effective as the loading density is increased.

(11) External Trench Barricade. The trench barricade concept was developed to perform the same function as conventional, free-standing, external barricades; i.e., to deflect the airblast and debris as it exits a tunnel portal after an internal explosion. The difference is that the tunnel portal opens onto the floor of a steep trench excavated into the mountainside, rather than opening directly out from the face of the mountain slope. The trench is open at one end for access to the portal. The height of the trench wall, and the fact that the trench is closed at one end, were expected to deflect more of the blast and debris upward, where it would then be distributed more equally in all horizontal directions. The 1/20-scale model tests of a trench barricade provided an average QD reduction of 67 percent, compared to identical tests without the barricade.

(12) Water Tamping of Detonations. Previous research by Sweden and the U.S. Navy indicated that a large mass of water in a confined detonation chamber could absorb a significant amount of the heat energy of a detonation (by rapid vaporization of the water), thereby cooling the detonation gasses and reducing the chamber pressure, which should reduce the external pressures and the QD. Eight experiments were conducted in the U.S. Phase 2 small-scale program to evaluate this phenomenon. In the first seven tests, latex containers of water were placed next to the explosive charges in the detonation chamber. In an additional test, the container was placed near the chamber exit, rather than next to the charge. Chamber loading densities of 1.7 to 5.0 kg/m^3 were tested with water/explosive weight ratios ranging from 0.7 to 3.3. Tests with a water/explosive ratio of 2.6 reduced the QD by an average of 50 percent. Surprisingly, the other four tests produced little or no noticeable reduction in the QD.

3.3 PHASE 3: INTERMEDIATE-SCALE TESTS.

3.3.1 Purpose.

The major research effort of the UAST program was performed in Phase 3. The experimental program consisted of 14 explosive tests at 1/8-scale in the ROK, and 13 tests at 1/3-scale in the U.S., all conducted in tunnels and chambers excavated in rock.

The objectives of the intermediate-scale tests were to:

- o Confirm or modify the fundamental relations between blast effects and tunnel/chamber geometries that were established by the small-scale experiments of Phase 2.
- o Refine those relations by conducting tests under more realistic conditions (i.e., that simulate detonations and the blast environments of actual underground magazines).
- o Obtain blast effects measurements that could not be made at small-scale.
- o Confirm blast effects scaling relations for larger explosive yields.
- o Examine performance of blast and/or debris control techniques at a larger (and more realistic) scale of testing.

Test sites were established for the intermediate-scale tests in both the U.S. and Korea. The U.S. site was located at the Linchburg Mine, near Magdalena, NM. Because of the steep mountain slopes in front of the mine entrance, the U.S. site did not provide a good area for measuring external airblast and debris hazards from detonations within the mountain. However, the 300-m length of the mine provided easy access to a test area in a moderately strong limestone rock, with a deep (over 100 m) rock cover. This represented an ideal site for conducting large detonation tests that require a strong rock containment, particularly for investigations of ground shock propagation and measurements of airblast attenuation along long tunnel lengths.

The ROK test site was located near Yeonchun, Kyungki-do, Korea. The test area was in a hard igneous rock, at the base of a small mountain ridge, facing a similar ridge across a narrow (approx. 100 m-wide) valley. Unlike the U.S. site, the topography of the mountain ridge at the ROK site did not provide sufficient rock cover depth for large detonations without extensive tunnel construction. However, the small, relatively level valley area in front of the ridge was ideal for recording the external airblast and debris effects from realistic detonations in scaled-down tunnel-and-chamber systems.

In view of the differences between the ROK and U.S. test sites described above, it was decided that the specific objectives of the Phase 3 test program should be divided between the U.S. and ROK efforts in a way that made the most beneficial use of each test site. Accordingly, the ROK Phase 3 tests were primarily designed to investigate the external airblast and debris hazard distances as a function of different components of the magazine design, with emphasis on:

- Blast/debris traps
- Tunnel constrictions
- Expansion chambers
- Blast-driven chamber closure blocks
- Dual tunnel exits
- External barricades

The U.S. Phase 3 tests were designed to place more emphasis on the blast effects internal to the underground complex, as a function of the characteristics of the explosion source and the tunnel/chamber system. For airblast, ground shock, debris, and thermal effects, these included:

- Chamber loading density
- Munition type
- Tunnel length
- Tunnel wall roughness
- Tunnel intersections
- Expansion chambers
- Storage chamber separation distance
- Self-sealing chambers

There was a deliberate overlap between the U.S. and ROK programs for some of the investigations, such as the effects of tunnel length, tunnel intersections, and expansion chambers.

This was done to allow direct comparisons to be made, and to ensure that the test results were consistent and compatible between the two experimental programs.

3.3.2 The ROK Phase 3 Program.

a. <u>Design and Construction of Intermediate-Scale Magazines</u>. The site selected for the ROK intermediate-scale test was an area covered with well-developed granite, in a military camp located in Yeonchun-gun, Kyungki-do. Test magazines were constructed by excavating tunnels at 1/8-scale, designated as the First to the Fifth Tunnels (Figure 3.8). There were one to three chambers in each tunnel. In the First and Second Tunnels, the width and height of the main tunnels were set to 1.2 m. For ease of excavation, the tunnels were first excavated to a larger size; a width and height of 1.8 m. The width and height were then adjusted to the final size of 1.2 m each by filling 0.6 m with gravel and concrete. Construction of the First and Second Tunnels revealed that this construction procedure was very difficult. For this reason, the finished height of the Third to the Fifth Tunnels was designed to be 1.8 m. The storage chambers were 3.8 m long, 1.9 m wide, and 1.8 m high.

All tunnels were originally designed to be equipped with chamber closure blocks, blast traps, expansion chambers, external barricades, and constrictions, in case it was determined to be necessary to test these features. On some tests, the debris-containment effect of specific damage-reducing features was investigated by placing artificial debris in front of the explosive charge in the storage chamber, and collecting the debris pieces inside and outside the tunnel after the tests. As in the small-scale tests, pressure gages were installed both inside and outside the tunnels. Figure 3.9 shows typical locations of airblast gages. An analysis of the results was made in the same fashion as in the small-scale tests. Additional details are given in References 24 and 25.

b. <u>Description of Tests and Results</u>.

(1) <u>Tests in the First Tunnel</u>. In the First Tunnel, one chamber was located on the left side and two chambers on the right side of the straight main entrance tunnel. Blast traps of the

same length as the width of the main tunnel were constructed directly across the main tunnel from the chamber entrances. Chambers 1 and 2 were equipped with closure blocks and entrance constrictions, while there was no hazard-reducing device in Chamber 3. The Type 1 closure block in Chamber 1 was a scaled-up version of a design, called the Magae Block, that proved to be effective in the Phase 2 small-scale tests. The Type 2 closure block in Chamber 2 was a heavier version of that in Chamber 1. The closure blocks tested in the ROK Phase 3 program were wedge-shaped boxes formed of welded steel plates, and filled with concrete. For investigations of the debris-reducing effect of the closure blocks, artificial debris consisting of short sections of steel rods (500 pieces of 50 g each; 150 of 100 g each; and 50 of 500 g each) were placed on a platform between the test explosive charge and the entrance of the chamber in each test.

Four tests were conducted in the First Tunnel--one each in Chambers 1 and 2, and two in Chamber 3. The first test in Chamber 3 was made with no hazard-reducing device. A concave external barricade was then constructed in front of the tunnel portal, and the second test in Chamber 3 was made. Figure 3.10 compares the measured peak pressures from the fourth test with the current DoD prediction. Values for the free-field pressure coefficient, a_w, and the relative hazard area, *RHA*, are listed in Table 3.1. Debris distributions recorded after the tests are listed in Table 3.2. The notable observations for the tests in the First Tunnel were: (a) the Type 1 closure block in Chamber 1 sealed the chamber entrance completely, (b) a part of the closure block in Chamber 2 failed, but the rest of the block partly covered the chamber entrance, and (c) the flow of explosion gas products from the tunnel portal was diverted 90° by the external barricade.

(2) <u>Tests in the Second Tunnel</u>. The layout of the Second Tunnel was basically the same as that of the First Tunnel. A Type 3 closure block was installed in Chamber 1, a Type 2 closure block in Chamber 2, and other hazard-reducing devices in Chamber 3. The Type 3 closure block in Chamber 1 was a design similar in principle to that of the Klotz Block. The Type 2 closure block in Chamber 2 was the same design as in the First Tunnel. Three tests were made in the Second Tunnel (one in each chamber). After the tests in Chambers 1 and 2, the main tunnel was diverted by 90° to a new entrance, and the original entrance of the tunnel was blocked. For the

test in Chamber 3, a trench barricade (see Section 3.2.4 c (11)) was constructed in front of the new tunnel entrance to compare its effectiveness with the concave portal barricade used on the First Tunnel. For those tests where the debris-containment effect of hazard-reducing devices was tested, artificial debris was located in the storage chambers in the same way as in the tests in the First Tunnel.

The notable observations for the tests in the Second Tunnel were: (a) the front steel plate of the Type 3 closure block in Chamber 1 was torn out and separated by the explosion, but the block effectively sealed the chamber opening; (b) the concrete floor near the constriction at the chamber entrance was ripped up by the blast from the Chamber 1 test and covered about half of the Chamber 1 access tunnel; (c) a welded part of the front steel plate of the Type 2 closure block was torn by the test in Chamber 2, but the block sealed the chamber entrance well; and (d) in the trench barricade test, the free-field pressure was independent of the azimuth angle from the portal, which was the same result observed with the concave barricade for the First Tunnel (Reference 26).

(3) Tests in the Third Tunnel. The layout of the Third Tunnel was complicated, consisting of the tunnel entrance, the main tunnel with a 45° bend and a 90° bend, an expansion (loading/unloading) chamber, two more 90° bends in the main tunnel, and a single storage chamber. Two tests were made in the Third Tunnel. The first test investigated the influence of the expansion chamber and the complicated tunnel layout on the debris distribution. Before the test, a total of 700 steel pieces of artificial debris were put in the storage chamber, and 450 pieces of 150 g each were placed in the expansion chamber. The locations of the artificial debris pieces were recorded after the detonation. Before the second test, three constrictions were installed between the bends of the main tunnel to reduce the tunnel cross-sectional area at those locations by 50 percent. The second test was to investigate the hazard-reducing effect of these constrictions. The free-field pressure coefficient a_w and the relative hazard area, *RHA*, for both tests are listed in Table 3.1. The debris distribution measured after the first test is listed in Table 3.2. The notable observations for the tests in Third Tunnel were: (a) the artificial debris in the expansion chamber did not travel far; most of it was deposited on the floor of the expansion

chamber; (b) most of the artificial debris in the storage chamber did not escape that chamber--that which did was deposited in the tunnel (none escaped to outside); (c) the relative airblast hazard area, *RHA*, in the second test (with constrictions) was determined to be 0.03, which was a 90 percent reduction of that in the first test (0.34), without constrictions (Reference 27).

(4) Tests in Fourth Tunnel. The Fourth Tunnel was originally a shotgun-type underground magazine with three constrictions in the main tunnel, of 12 m total length. The objective of the first test was to investigate the blast-reducing effect of constrictions. After the first test, the magazine was remodeled to have a tunnel layout similar to that of a full-scale, prototype underground ammunition storage. To the right side of the existing main tunnel, a second entrance, a second main tunnel, and a storage chamber were added. The constrictions in the existing main tunnel were removed, and the original main tunnel was designated as the new left main tunnel. The right and the left main tunnels were parallel, and were connected by an expansion chamber near the tunnel entrances, and by a main cross tunnel at their back ends (see Figure 3.8).

In the first test, the pressures measured inside and outside the magazine were almost the same as predicted by the existing DoD standards, which led to the conclusion that constrictions are not effective in reducing blast for a straight, shotgun-type magazine. From the second test, the free-field pressures in the left and right tunnels were similar, demonstrating that the free-field pressure is not highly sensitive to the location of the explosion source in an underground complex. There was a significant difference in arrival time of the blast waves exiting from the two tunnel portals. As a result, the peak pressures of the external blast waves were not superimposed (Reference 28).

(5) Tests in the Fifth Tunnel. The Fifth Tunnel was a curved tunnel with an entrance portal at each end, and three storage chambers located along the central section (Figure 3.11). Where the entrance tunnel to each storage chamber intersected the main tunnel was a space designed to be used as loading/unloading area and as a blast/debris trap. For Chambers 1 and 3, closure blocks and entrance constrictions were constructed. The closure blocks were the Magae

type (Type 2) similar to those used in Chamber 2 in the First Tunnel. Since the height of the chamber access tunnels was increased to 1.8 m, the height of the closure blocks was increased accordingly. Chamber 2 had no closure block and no constriction. In front of the right tunnel portal, an external barricade was constructed to evaluate the blast- and debris-reducing effect of an external barricade, by comparing the free-field pressure and debris distribution from the barricaded right portal to that from the left portal, where there was no barricade.

Three tests were conducted in the Fifth Tunnel. The results are compared with predictions using the current U.S. DoD safety standards in Figure 3.12, for internal pressures, and 3.13 for free-field pressures. Debris distribution data recorded after tests in Chambers 1 and 3 are listed in Table 3.2. In the first test (in Chamber 1), the Type 2 closure block sealed the chamber entrance, but the upper part of the constriction at the chamber entrance collapsed, and blast escaped through this hole. In the second test (Chamber 3), the Type 2 closure block sealed the chamber entrance well. In all three tests, the blast wave from the right portal was diverted upward by the barricade (as recorded by photography), and did not influence as much area in front of the portal as it did at the left (unbarricaded) portal (Reference 29).

c. Supporting Studies.

(1) Small-Scale Constriction Test for Design Supplement. To investigate the blast-reducing effect of constrictions, steel constrictions were made and added to the 1/30-scale steel model magazine used in the ROK Phase 2 small-scale tests. Since the effect of a constriction was expected to vary depending on its location (or more precisely, the pressure incident upon it), tests varying the location of a single constriction and tests with two constrictions were conducted. The constriction locations tested included: near the entrance of the storage chamber (Chamber Constriction); at the middle of the main tunnel (Mid-tunnel Constriction); and near the portal (Portal Constriction). The tests with two constrictions were designated as Dual Constriction tests. For the Mid-tunnel Constriction and Dual Constriction designs, two tests of each were made, with C-4 explosive charges of 0.46-kg (chamber loading density of 4 kg/m^3) and 1.9 kg (chamber loading density of 16.5 kg/m^3). In the Chamber Constriction and Portal Constriction tests, only one test of each was made, with a 1.9-kg C-4 charge (16.5 kg/m^3).

The coefficient a_w and the relative hazard area, *RHA*, were determined based on the test results by using Equations (3-2) and (3-4). For the smaller detonations, the value of a_w was 2.77 for the Mid-tunnel and the Dual Constrictions. For the larger tests, the value of a_w was 1.80 for the Mid-tunnel Constriction, 1.83 for the Chamber Constriction, 2.22 for the Portal Constriction, and 2.39 for the Dual Constrictions. These values showed that the blast-reducing effectiveness of a constriction is a function of its location, and that its effectineness increases as the incident pressure decreases.

(2) Numerical Simulation of the Motion of Self-Closing Blocks. To simulate an explosion inside an underground storage chamber equipped with a Magae-type self-closing block, a hybrid technique was used to calculate the block motion, assuming that the only forces applied to the block are the blast pressure and the friction between the block and the wall/floor. Pressure-time histories at several points around the block were obtained from a two-dimensional hydrodynamic code (HULL code) calculation. The motion of the block was obtained by solving Newton's equation of motion, assuming that the pressure-time histories on a moving block were identical to those calculated for a stationary block.

This numerical study showed that the friction between a block and the floor owing to the block mass was negligible, but the friction between a block and the side wall, owing to blast pressure, affected the block motion very much. A block installation should be designed to minimize this effect as much as possible.

(3) Contract Research. A contract study titled "The Study on the Structural Supporting Methods in the Design of the Underground Ammunition Storage Facilities," was conducted by LTC Kim Oon-Young of the Korea Military Academy (Reference 30). The following is an abstract of this research:

> "Supporting methods for underground ammunition storage facilities and related engineering technologies are discussed. Rockbolting and shotcrete systems are more desirable, in terms of economy and structural stability, than a steel rib

supporting system. For the most successful application of a rockbolt system, the rock mass classification is very important. The Q-system of classification normally is a better method than the RMR system, because the Q-system can directly provide the specific supporting guide. Systematic rockbolting and wire-mesh reinforcement is recommended for better stability under dynamic loading conditions, such as those resulting from an accidental explosion. The establishment of the weighing method using the ESR (Excavation Support Ratio) value is highly recommended for economy of the supporting work. Finally, the measurement and evaluation of the stress and displacement of the rock surface and rock bolts are necessary in order to confirm the tunnel stability and evaluate the need for additional support."

3.3.3 The U. S. Phase 3 Program.

a. <u>Intermediate-scale Test Facility</u>. The U.S. Phase 3 Program consisted of a series of thirteen explosive tests conducted in an underground test area in the Linchburg Mine, near Magdalena, NM. The test area was located some 250 m inside the mine, where the rock cover depth of approximately 100 m would ensure that there would be no influence of the ground surface on the largest detonations.

Figure 3.14 shows the location of the test drifts and chambers excavated in the Linchburg Mine. With the exception of Test 1, which was fired in the existing Linchburg Mine tunnel, all tests were conducted in the chambers of the North Test Drift. Figure 3.15 shows the locations of the 13 tests. A summary of the test parameters for each test is given in Table 3.3. Composition B explosive was used in all tests except Test 13, which used nitromethane. Most of the charges were constructed of surplus M15 mines stacked in horizontal columns.

Airblast measurements consisted primarily of side-on overpressures recorded by gages emplaced flush with the tunnel floor, or at the ground surface immediately outside the portal of the Linchburg Mine. Inside the chambers, the gages were placed in the center of the chamber walls. Stagnation (or total) pressures were measured in the tunnels and outside the portal using

probe-type mounts located approximately 0.75 m above the centerline of the tunnel floors. Figure 3.16 shows the airblast gage locations in the North Test Drift area.

Ground shock measurements were made on selected tests. To record the free-field ground shock, accelerometers were installed in a vertical hole drilled from the center of Chamber 4 to the surface, and in a horizontal hole drilled from Chamber 4 to the south end of the North Test Drift. Accelerometers were also placed in horizontal holes drilled from Chamber 2 south to Chamber 1 and north to Chamber 3. Figure 3.17 shows the ground shock gage layout. Additional details are given in Reference 25.

b. Test Results.

(1) Airblast--Effect of Tunnel Wall Roughness. Test 1 was a 14.7-kg charge detonation in the Linchburg Mine to investigate the effect of the rough wall of the mine tunnel on airblast propagation. Two SHARC computational models -- one with smooth tunnel wall and one with rough walls -- were evaluated against the test results. The rough wall profiles were developed from measurements of the mine tunnel height and diameter at 1-m intervals of distance. In both calculations, the walls were assumed to be rigid and perfectly reflecting. Additional predictions were made using the BLASTX PC code. The SHARC calculation for a smooth-wall tunnel provided peak overpressures that were good approximations of the measured data close-in to the charge, but over-predicted the peak pressure at the mine portal by almost an order of magnitude. The SHARC model for a rough-wall tunnel over-predicted the measured values for most of the Linchburg Mine tunnel length, but the error was less than a factor of two. The BLASTX model under-predicted the peak pressures in the tunnel by a factor of about two.

The measured peak pressures for Test 1 ranged from 1,020 kPa at 7.4m from the charge, to 22 kPa at 147m. The peak positive impulse values, obtained by integrating the recorded pressure-time histories, gradually decreased from 15 kPa-sec at 7.4 m from the charge to 3.8 kPa at 147 m.

(2) Airblast--Variation with Loading Density. Four tests, with loading densities of 1.1 to 37.3 kg/m^3 (charge weights of 70 to 2,500 kg) were conducted in Chamber 4 to study the effects of chamber loading density on the airblast propagation throughout the underground magazine facility and into the free field (outside the mine portal). The peak overpressure data from these tests are plotted versus distance from the rear wall of Chamber 4 in Figure 3.18.

Peak overpressures at selected distances along the main airblast flow path are plotted as a function of chamber loading density in Figure 3.19a. This graph indicates that the peak pressure, P, can be related to the loading density, Q, by the expression

$$P = 7.25\ Q^{0.7} \tag{3-9}$$

Peak impulse values at the same distance are also plotted versus chamber loading density in Figure 3.19b. This graph indicates that the peak impulse, I, can be approximated by the expression

$$I = 35\ Q^{1.2} \tag{3-10}$$

where I is in kPa-secs and Q is in kg/m^3

(3) Airblast--Effect of Tunnel Length and Intersections. One of the reasons for locating the test area deep within the Linchburg Mine was to provide a long distance between the detonation chamber and the tunnel portal, in order to observe how the airblast pressure and impulse attenuated as a function of tunnel length. For Test 6 in Chamber 4, which had a chamber loading density of 37.3 kg/m^3, the peak pressures recorded along the airblast flow path (to the tunnel portal) had a consistent attenuation rate of $R^{-1.62}$, where R is the distance from the chamber. In general, the 90-degree intersections had little or no effect on the peak pressure attenuation rate along the 300-m length of the flow path.

(4) Airblast--In Adjacent Storage Chambers. An important concern for the use of multi-chamber underground magazines is the possibility that munitions in one chamber (an "acceptor") will be sympathetically detonated by blast effects from a detonation in a nearby chamber (the

"donor"). It is expected that each chamber will have a heavy door that will normally be closed and able to protect the chamber contents from external blast effects. To determine the level of the blast pressures intruding into an acceptor chamber in a worst case situation, where the door of the acceptor chamber is open, pressure measurements were made in other chambers along the North Test Drift from the 37.3 kg/m^3 detonation of Test 6 in Chamber 4.

The average peak pressure recorded in Chamber 2, located 37 m from Chamber 4, was 1,472 kPa (average of four gages), or roughly 65 percent of that at the same tunnel distance along the main flow path. The side-on pressure in Chamber 1, about 60 m from the detonation, was 1,120 kPa, which was about 85 percent of that at the same distance along the flow path.

(5) Airblast--Reduction by Expansion Chambers. Previous research in Norway and other countries has indicated that expansion chambers, located between a detonation and the tunnel portal, can reduce airblast at the portal by as much as 30 percent. To provide a large-scale evaluation of this effect, an expansion chamber was excavated in the North Test Drift after Test 6 in Chamber 4. The expansion chamber was 6 m wide, 22 m long, and 2 m high, and had two exits (to simulate the geometry of an ammunition loading/unloading chamber in a large underground magazine complex). After the expansion chamber was completed, Test 7 was conducted in Chamber 4 to provide data that could be compared to that from Test 6, in order to evaluate the effect of the expansion chamber on both airblast and debris transport. The data showed only a very minor reduction (a few percent) in the peak pressure level after the blast passed through the expansion chamber. However, for Tests 10, 11, and 12, which were conducted later in Chamber 1 with smaller charge weights (roughly 340 kg each, versus 2,570 and 2,890 kg for Tests 6 and 7), there was a 40 percent reduction in the peak pressures beyond the expansion chamber. These results support the hypothesis that expansion chambers are more effective in reducing pressures from detonations of lower loading densities, which are more shock-driven, than from detonations of higher loading densities, which are more gas-pressure driven.

(6) Airblast--Effect of Munition Type (Case Thickness). It has long been held that heavy-cased (or "robust") munitions, such as 155-mm projectiles, GP bombs, etc. produce less

airblast than bare charges, due to the explosion energy required to rupture the heavy steel casing. For detonations in free air, the reduction in peak pressure is typically about 30 percent.

Tests 10, 11, and 12 were conducted in Chamber 1 to determine if airblast in the semi-confined environment of an underground magazine would be reduced by a similar amount. The explosive charges were constructed of cast Comp B blocks (bare charge), M-15 mines (light-cased munitions), and 155-mm artillery rounds (heavy-cased munitions) for Tests 10, 11, and 12, respectively. Each charge had an NEW of 340 kg (loading density of 5.4 kg/m^3). There was little difference in the recorded airblast levels between the bare charge and M-15 mines (light-cased munitions). Within the main portion of the tunnel system, however, the peak pressures produced by the detonation of the 155-mm artillery rounds were about 40 to 50 percent lower than the pressures from the bare charge and the M-15 mines. This difference dropped to approximately 20 percent at the Linchburg Mine portal. An examination of the plot of impulse data indicated that the peak impulse produced by the 155-mm projectile (heavy-cased) charge was approximately one-half of that from the bare charge detonation throughout the tunnel system, including gage positions near the Linchburg Mine portal.

(7) Ground Shock--Damage to Adjacent Chambers. The current DoD safety standards specify scaled separation distances of 1.4 to 2.0 $W^{1/3}$ (where W is the NEW in kilograms) between adjacent storage chambers, in different rock types, to prevent damage to munitions in one chamber by spalling of the chamber walls due to ground shock loads from a detonation in an adjacent chamber. For the limestone rock of the Linchburg Mine, the current standards recommend a separation distance of 1.7 $W^{1/3}$. Test 8, with a loading density of 46.5 kg/m^3 , was conducted in Chamber 2 to provide more realistic data on minimum chamber separation distances. The scaled inter-chamber distance was 1.02 $m/kg^{1/3}$ between Chambers 1 and 2, and 2.18 $m/kg^{1/3}$ between Chambers 2 and 3, which were 60 and 150 percent, respectively, of the values required by the current standards.

Peak particle velocity data from Test 8 are plotted versus distance from the center of the detonation chamber in Figure 3.20a. A least squares fit to the data shows that, for Test 8, the peak particle velocity, ν (in m/sec), can be related to distance, R (in m), by the expression

$$\nu = 834\, R^{-2.3} \tag{3-11}$$

Also shown in Figure 3.20a is the minimum chamber separation distance required by the current standards to prevent damage to stored munitions by rock spall in an adjacent chamber. No spall damage was observed either in Chamber 1 or Chamber 3 from the detonation of Test 8 in Chamber 2. Therefore it was concluded that the 1.7 $W^{1/3}$ separation distance required by the current standards is overly conservative for moderately-hard to hard rock, such as the Linchburg limestone. The data indicates that a separation distance of 1.0 $W^{1/3}$ is sufficient to prevent damage in this type of rock.

(8) Ground Shock--As a Function of Loading Density. The guidelines given in the current safety standards state that ground shock produced by explosions in underground magazines will vary as a function of the explosion "decoupling" factor, which is a relative measure of the efficiency with which the explosion energy is transmitted into the surrounding rock. The smaller the explosive charge in a given chamber volume, the more the explosion energy is decoupled from the rock. Thus, the decoupling factor is defined as a function of the loading density.

Since all the chamber tests in the U.S. Phase 3 series were decoupled detonations, an additional test was conducted to provide a ground shock baseline from a fully-coupled detonation in the Linchburg limestone. Test 13 was a small, fully-coupled, 116-kg charge of nitromethane explosive detonated 7.4 m below the expansion chamber floor in a 40-cm diameter hole. Ground shock measurements from this "calibration" test were used as the baseline for evaluating the effect of loading density on ground shock levels in the surrounding rock. In Figure 3.20b, the peak particle velocity data from the Phase 3 tests is plotted versus scaled distance (i.e., scaled by the cube root of the NEW). Cube root scaling collapses the data from the decoupled tests to a nearly linear relation. The decoupled data is clearly separated from the fully-coupled data. The chamber

loading densities for the decoupled group ranged from 1.1 kg/m^3 to 46.5 kg/m^3, which should represent of a realistic range of storage densities. Since the data sets for the different decoupled tests essentially overlie each other, it appears that variations in the energy decoupling factor, within this range of loading densities, has no effect on peak ground shock at a given scaled distance. Regardless of the loading density (within this range), the decoupled detonations appeared to produce scaled peak particle velocities that were only about 20 percent of those from the fully-coupled detonation (Reference 31).

(9) Ground Shock--Inhabited Building Distance. The Inhabited Building Distance criterion for ground shock given in the current DoD standards is a peak particle velocity of 23 cm/sec (9 in./sec), when particle velocity data is available for the site of interest. This value occurred at a range of about 35 m from the center (or 34.4 m from the nearest wall) of the Test 8 detonation chamber. When particle velocity data are not available for a site of interest, the standards require use of the following equation for determining the ground shock Inhabited Building Distance (D_{ig}):

$$D_{ig} = 5.41 \ f_g \ W^{4/9} \tag{3-12}$$

where W is the NEW in kilograms, and f_g is the decoupling factor, which can be calculated as a function of the chamber loading density, Q, in the manner:

$$f_g = 0.116 \ Q^{0.3} \tag{3-13}$$

For Test 8, the Inhabited Building Distance computed from these relations was 70.5 m. Thus, the current criterion over-predicts the D_{ig} by approximately a factor of two for this rock type and range of loading densities.

c. Supporting Studies.

(1) Cost-Benefits Analysis for Underground Magazines at Army Installations in the U.S. MTA, Inc. performed a contract study for WES to evaluate the benefits that could be realized by the construction and use of underground ammunition storage facilities at eight typical Army bases in the U.S. (Reference 32). The study considered operational and environmental factors, as well as economics (based on a life-cycle cost model). From a pure cost standpoint, the study

concluded that the least economical approach at all bases was to abandon existing above-ground magazines and replace them with underground facilities. On the other hand, the construction of underground magazines for *new* storage requirements, while retaining the existing above-ground facilities for present storage, was only slightly more costly than the exclusive use of above-ground magazines. It is important to note, however, that this study was performed using the hazard areas for underground storage as defined by the *current* standards, with the associated large real estate requirements. The economic balance should shift strongly in favor of underground magazines if the lower real estate costs of the reduced QD's established by the UAST program are used.

In all cases, the operational and environmental considerations were found to strongly favor the use of underground magazines -- enough to well offset any economic disadvantages. In summary, the analysis indicated that the most overall beneficial alternative at the installations examined would be to abandon the present above-ground magazines and replace them with underground storage facilities.

(2) Computer Modeling of Airblast Hazards From Explosions in Underground Magazines. A number of studies were performed, by WES, ADD, and other organizations, to develop and/or evaluate computer models as a tool for predicting explosion airblast levels inside and outside of underground magazines. It was established that hydrocode (e.g., SHARC) calculations using 2-dimensional, plane geometry grids provide reasonable approximations of airblast flow through the underground facilities, at much less cost than the use of 3-D grids, and with much more accuracy than 2-D axisymetric grids (Reference 33). This type of model appears to be an excellent tool for examining the relative effect on airblast of different tunnel and chamber configurations (References 21, 34, and 35). However, the accuracy of hydrocode predictions of airblast peak pressures is not good after the shock front has traveled 10 tunnels diameters or so beyond the detonation chamber (Reference 36).

The less complex AUTODYNE code appears to provide good *relative* predictions, with significantly less cost and effort than required by hydrocodes (Reference 37). The BLASTX PC computer model is even more convenient and inexpensive to run, and actually provided more

accurate predictions of airblast peak pressures in an underground facility than did the hydrocodes (Reference 38).

(3) Effect of Rough Tunnel Walls on Fragment Transport. Previous large-scale tests by the KLOTZ Club of accidental explosions in simple underground magazines showed that steel fragments from the munition casings was one of the most far-reaching hazards in front of the tunnel portal (which led to the name, "shotgun" magazine). The Denver Research Institute was contracted by WES to determine how more complex magazine designs, with tunnel bends, intersections, and rough tunnel walls, would affect the transport of such fragments from a detonation point.

A series of laboratory tests were conducted in which steel cubes weighing 15, 30, and 45 grams were fired at limestone and granite surfaces at velocities of 1,200 and 1,800 m/sec, and at angles of impact of 30, 45, and 60 degrees (Reference 39). The results showed that, regardless of the impact angle, about 90 percent of the fragments's incident kinetic energy was lost, and the fragment itself was usually fractured by the impact.

Two additional tests were conducted by detonating single, 155mm, M107 artillery rounds nose-down on the floor of the Linchburg Mine (Reference 40). One witness panel was set up in a direct line- of-sight in one direction, and another at the same distance in the other direction, but around a slight bend in the mine tunnel. The results showed that ricochets off the rough tunnel walls tended to focus the fragment dispersion down the tunnel, with fragment densities 15 to 25 times the densities reported (at the same distances) from free-field arena tests. However, the fragments lost most of their energy by the first impacts with the tunnel walls. No fragments reached the second witness panel, which was not in a line-of-sight of the detonation.

The study demonstrated that tunnel bends and intersections and rough (exposed rock) tunnel walls will greatly reduce the kinetic energy of fragments after first impacts with the walls. These tunnel design features should effectively eliminate the risk of secondary detonations of

munitions in other chambers due to fragment impacts, and will greatly reduce the fragment throw distances in the free-field that are normally associated with "shotgun"-type magazines.

(4) <u>Vulnerability and Security of Underground Magazines</u>. When the underground storage concept was selected by the ROK and U.S. review committees for this program, one of the important advantages was the belief that much greater protection of the ammunition stores would be provided. This issue was addressed by WES as a supporting study for the UAST program, using test data and analyses developed under another research program. Although the information used cannot be included in this report, the following paragraphs describe the general findings of the security/vulnerability assessment.

Two types of enemy action were considered--terrorist activities (or sabotage), and combat strikes with artillery and air-delivered weapons. Above-ground storage sites have very large perimeters that must be fenced and guarded against intrusion. One of the great advantages of underground storage is the fact that the stored ammunition can only be reached through the tunnel portals. Consequently, a major increase in security is achieved, with the presence of a single guard post at the main portal, and the use of strong portal doors that are highly resistant to forced entry. For large facilities with dual portals, the portals can be closely spaced so that both can be monitored by a single guard post.

The WES vulnerability analysis concluded that enemy attacks with surface-to-surface weapons, such as mortar, artillery, or missiles, is almost totally ineffective against underground magazines in rock. The worst effect is the potential damage to a portal door by blast and/or fragments. At large facilities that have internal loading/unloading areas, personnel and transport trucks are only vulnerable for a very short period, as they pass in or out of the portals.

Weapons delivered by aircraft can potentially cause some damage by three different methods. First, a bomb delivered with great precision by an aircraft flying a low-level, shallow-dive attack profile could penetrate a portal door and travel some distance into an entrance tunnel before detonating. In a shotgun-type magazine, the blast and/or fragments could damage or

detonate the stored munitions. This type of attack can be defeated, however, by (a) a portal barricade that shields the tunnel entrance, (b) locating the portal so that the extended tunnel axis is directed toward an adjacent ridge or hill that prevents a low-level flight approach, or (c) having a sharp bend or intersection in the tunnel so that the bomb will impact a tunnel wall and detonate at a safe distance from the underground operating or storage area.

The other two attack methods require delay-fuzed, penetrating bombs that can be delivered against the area in front of or above the portal. Such a detonation immediately above the portal could cause the portal, or the tunnel area directly behind the portal, to collapse. A crater-forming detonation from a penetrating bomb strike farther up the slope above the portal could cause a slide of rock debris to be deposited in a pile in front of the portal entrance. A similar detonation in front of the portal could produce a large crater.

None of these three methods pose any danger to the ammunition stores or operations inside the facility. However, the debris piles, or a crater at the portal, would probably be an impassable obstacle to munition transport vehicles. The facility would then be effectively shut down for a period of minutes or hours, depending on the time required to clear the rubble piles or fill the crater, either by labor or with heavy equipment.

In summary, underground magazines located in moderately-strong to strong rock can easily be designed to be relatively invulnerable to any attack with non-nuclear weapons. The most serious problem for a properly designed facility is the risk of access denial for a period of minutes to hours, if earth-moving equipment is available for rubble removal, or hours to days, if it is not.

3.4 PHASE 4: VALIDATION TEST AND BARRICADE EVALUATION STUDY.

3.4.1 Validation Test.

a. <u>Purpose</u>. The principal research efforts in Phase 4 were the Validation Test and the Barricade Evaluation Study. The purpose of the Validation Test was to evaluate, in a large-scale test, the structural performance and explosion hazard reductions provided by a blast-driven,

chamber closure block design developed by the ROK in Phases 2 and 3 of the UAST program. The Magae block, along with other hazard reduction features for underground magazines, was tested at 1/30 and 1/8-scale in the ROK Phase 2 and Phase 3 programs, respectively. The closure block however, was the only feature investigated in the UAST program whose performance was strongly influenced by its mass and strength. Since these could not be adequately scaled in the Phase 2 and 3 tests, it was decided that a 1/3-scale test of the Magae block was needed to verify that it would perform as well under more realistic loading conditions as it did in the ROK small-scale and intermediate-scale tests.

b. Test Description. The Validation Test was conducted at the Linchburg Mine site of the U.S. Phase 3 Intermediate-Scale Test Program, near Magdalena, NM (see Figure 3.15-3.16). Chamber 2, which was relatively undamaged from the Phase 3 tests in 1994, was reconfigured by constructing an angled front wall of the chamber with concrete. A constricted chamber entrance, 1.0 m high and 1.0 m wide, was constructed where the original, 1.5-m high, 1.5-m wide access tunnel entered the chamber. Figure 3.21 shows the shape and dimensions of the Validation Test chamber, and the positions of the closure block and the explosive charge for the test.

The closure block was a concrete-filled, trapezoidal-shaped box made of 12.7-mm thick steel plates welded together. No. 5 steel reinforcing bars were placed at 225mm vertical and horizontal spacings in a three-dimensional grid to strengthen the interior concrete (Figure 3.22). Three steel W8x40 H-beams were welded behind the front face of the block to help bridge across the access tunnel opening when the block was driven by the explosion to impact against the front wall of the chamber.

The explosive charge for the Validation Test was constructed of M15 AT mines (identical to those used in the U.S. Phase 3 tests) and seven pallets of 155mm M107 artillery projectiles. All contained Composition B explosive, with a total NEW of 1,955 kg. The chamber loading density was 30 kg/m^3, which matched the ROK 1/8-scale, Phase 3 tests of the Magae closure block design. The artillery rounds were used to provide a source of munition fragments, in order to evaluate the block's effect on debris transport.

c. Test Results. The Validation Test was conducted on 4 April 1996. Excellent data was obtained on airblast pressure histories, from the detonation chamber to the portal of the Linchburg Mine.

The closure block did not survive as predicted, and was completely destroyed in the test. Pieces of the steel and concrete debris were found in the debris trap outside the test chamber, in the North Test Drift (one piece was found near the entrance to Chamber 3), and in the debris trap and at other locations in the expansion chamber.

The two accelerometers placed in the closure block produced excellent records of the early motion of the block. As shown in Figure 3.23, the closure block apparently rotated counter-clockwise as it moved forward to block the chamber entrance. The northwest corner of the block struck the chamber wall approximately 27 msec after detonation and rebounded. Based on the observed wall damage and the accelerometers records, it was apparent that the block impacted the concrete wall on the south (right) side of the chamber entrance with enough force to shatter the concrete. Photographic evidence in support of this conclusion is shown in Figure 3.24. Lines, superimposed on the photo, outline the location of the chamber entrance before the detonation, and the missing section of the wall.

It is theorized that the remaining wall area around the entrance was insufficient to support the block against the extreme force applied by the chamber pressures. The block, which had probably been severely cracked by the blast and wall impacts, then failed in bending, and was broken into pieces as it was pushed through the enlarged chamber entrance by the blast pressures.

The influence of the closure block motion on the airblast history recorded immediately beyond the chamber entrance area is shown in Figure 3.25. Before the block moved a significant distance, the initial shock wave traveled around the block and into the access tunnel. The shock wave arrival time (7.81 msec) at Gage 19 is indicated by the symbol (a) on the plot. Typically, the peak shock pressure decays exponentially until the arrival of the detonation gas pressure phase. As the closure block began to close the chamber entrance, the gas flow from the test chamber was

temporarily choked off. The effect of the temporary closure was a decrease in gas pressure beginning at approximately 50 msec (b). Later, the break-up of the closure block allowed the gas flow to resume, which is evidenced by an increase in pressure (c). The erratic pressure behavior beginning at (d) was probably caused by closure block debris as it passed Gage 19.

d. <u>Hazard Reduction Performance of the Closure Block</u>. The Validation Test was conducted in Chamber 2 at a chamber loading density of 30 kg/m^3. This was the only U.S. experiment involving a closure block. During the U.S. Phase 3 tests, Test 8 was also detonated in Chamber 2, but with a larger chamber loading density (46.5 kg/m^3). Test 7 was detonated in Chamber 6, with a loading density of 39.5 kg/ m^3 at a slightly greater distance from each gage position (see Figure 3.16). Although a direct comparison of tests with and without a closure block cannot be made for *identical* conditions, Tests 7 and 8 were sufficiently similar to the Validation Test to clearly indicate the effect of the block as a hazard mitigator. A comparison of pressure-time histories from Tests 7 and 8 and the Validation Test show that the basic character of the airblast waveform was, in fact, strongly degraded by the closure block.

Figure 3.26a compares the airblast waveforms from the three tests as recorded by Gage 17, located about 17 m (10 tunnel diameters) from the test chambers. The strong, early-time peak shock pressures that characterize the waveforms from Tests 7 and 8 is completely missing from the Validation Test record. This effect was clearly evident at all of the downstream gage stations. Figure 3.26b shows the records from the three tests at a distance of 60 tunnel diameters, where the Validation Test waveform has less than half the peak pressure and impulse of the similar tests without closure blocks.

The Validation Test results were also compared to the results of the ROK's Phase 3 tests of closure blocks at 1/8-scale. During one of these tests, a closure block failed under the blast load, in a similar manner (although not as severely) as the block in the Validation Test. Figure 3.27 compares the pressure histories recorded at a distance of 14 tunnel diameters from the detonation chambers on three of the ROK Phase 3 tests, all conducted in the First Tunnel with chamber loading densities of 30 kg/ m^3. These were Test T1C3, with no closure block; Test

T1C1, with a successful (undamaged) closure block; and Test T1C2, where the closure block failed under the impact and blast pressure. The reduction in the pressure waveform produced by the failed block, compared to the test with no block, is almost identical to the reduction observed on the Validation Test.

Figure 3.28 compares external (beyond the tunnel portal) airblast records from the same three tests. The record shown for each test was that which had a peak airblast pressure closest (of all external measurements) to the 1.2 psi (8.3 kPa) criteria for the Inhabited Building distance QD given in the current safety standards. The undamaged closure block in Test T1C1 reduced the IBD from 68 m to 24 m. The failed closure block in Test T1C2 produced a smaller, but still significant reduction in IBD, from 68m to 36 m, or about 50 percent, which would provide a 75 percent reduction in IBD area.

e. **Conclusions**. Although the Magae-type closure block did not fully perform as designed, it produced significant reductions in the peak airblast pressure outside the detonation chamber.

The closure block failed structurally under the explosion loading. This failure was apparently due to the preceding failure of a section of the concrete wall on one side, and above, the chamber access tunnel, after impact of the block against the end wall of the chamber. The failure of the tunnel wall greatly increased the unsupported area on the front face of the block, allowing it to fail in bending, and then break up under the force of the chamber pressures.

Comparisons of the 1/3-scale Validation Test results with previous ROK tests at 1/8-scale show similar results when the closure block failed. However, the inertia of the block, both before and after failure, was sufficient to retard the escape of the blast pressures significantly, resulting in a 50-percent reduction in the peak pressures and the QD_{IB}, and a 75-percent reduction in the QD_{IB} area. These reductions should be even greater at full scale, due to the proportionally greater mass and inertia of a full-scale closure block. The closure block was also effective in obstructing the transport of fragments from the detonating munitions.

3.4.2 Barricade Evaluation Study.

a. Purpose. Portal barricades were among the hazard control concepts tested at 1/8-scale in the ROK's Phase 3 intermediate-scale tests. The barricades were found to be very effective in stopping debris and diverting the airblast that issued from the portals (Reference 25). It was not practical, however, to vary the barricade parameters (size, shape, location, etc.) in the intermediate-scale tests because of the great cost involved in testing one barricade, and then destroying it in order to construct another to test a design variation.

Since the debris was focused within a narrow dispersion area, it was not difficult to predict the effectiveness of other barricade configurations in stopping debris. The propagation of airblast beyond the portal, and its interaction with a barrier, is much more complex, however. Experience has shown that airblast effects can be scaled with good accuracy in small-scale explosion tests. Therefore, a series of 1/30-scale tests of portal barricades was conducted by the ROK in Phase 4 to provide the needed data.

The test objectives were to determine the barricade's effect on airblast in the free-field (i.e., beyond the tunnel portal) as a function of (1) the NEW of the detonation, (2) the barricade shape, (3) the width and height of the barricade, and (4) the barricade standoff distance from the portal.

b. Test Procedure. For the barricade tests, the same steel magazine model employed in the ROK small-scale tests of Phase 2 was used. The model storage chamber had a volume of $0.115m^3$, and the tunnels leading to the portal were steel pipe with an inside diameter of 19.2 cm. Composition C-4 was used as the test explosive.

The barricades were made of 2.54 cm-thick steel plate, and consisted of a vertical section, representing the front face of the barricade, welded to a horizontal base plate. The barricades were held in position in front of the portal by spikes driven into the ground through holes in the base plate. Figure 3.29 shows the standard "Type I" concave barricade used in most of the tests. Side-on airblast pressure histories were recorded by gages mounted flush with the tunnel wall or

flush with the ground surface beyond the portal. The external gages were located along the extended tunnel axis and along radial lines from the portal at azimuths of 30, 60, and 90 degrees from the extended tunnel axis.

c. **Test Results**.

(1) Effect of NEW. Five tests were conducted with charge weights of 0.03 to 1.0 kg (loading densities of 0.25 to 8.7 kg/m^3). The Type I barricade was used at a standoff distance of one tunnel diameter. The overpressure at the tunnel portal, P_w (in kPa), could be described by the equation

$$P_w = 1{,}770\ (Q/V_e)^{0.45}$$

where Q is the NEW in kg and V_e is the shock-engulfed volume of the tunnel/chamber system. The free-field pressure, P, at a distance R (in meters) from the portal along the extended tunnel centerline could be expressed by

$$P_w/P = a_w\ (R/D)^{1.35}$$

where D is the tunnel diameter at the portal and a_w is a coefficient whose value is determined by the effect of a blast-reducing feature (in this case, the barricade). As shown in Figure 3.30, the value of a_w decreased as the portal pressure measured in these experiments, P_e, was increased. Since P_e was directly related to the NEW, the results indicate that the barricades effectiveness will decrease as the NEW increases.

Figure 3.31 shows the values of P_w/P as a function R/D_t for the test with an NEW of 0.4 kg, where the value of P is set to the QD_{IB} peak pressure criterion of 8.2 kPa given in the current safety standards (Reference 1). The peak pressures measured beyond the barricade, along the extended tunnel centerline, were about 50 percent of the those predicted by the equation in the current standards (solid curve in Figure 3.31). As can be seen in the figure, however, the free-field pressures along the 30, 60, and 90-degree azimuths did not vary significantly from those along the extended tunnel centerline (0-degree azimuth). The results of the tests therefore

indicate that the equation given in the current standards to calculate range to the IBD, which is dependent in the azimuth angle θ,

$$R = D[(P/P_w)\{1 + (\theta/56)^2\}]^{-1/1.35}$$

does not apply when a barricade is used. Since the QD_{IB} area becomes a circle centered at the portal, the barricaded IBD distance, R_{bar}, can be expressed as

$$R_{bar} = D\,(a_w P/P_w)^{-1/1.35}$$

where a_w is a function of the barricade configuration. Figure 3.32 shows the QD_{IB} area that was defined by the Type I barricade test with a 0.4 kg NEW, compared to that predicted by the current DoD safety standards.

(2) Effect of Barricade Shape. Figure 3.33 shows the four types of barricades tested in the Barricade Evaluation Study. Type I is concave toward the tunnel exit, so that debris impacting the barricade cannot escape to the free field. This type was also employed in the ROK Phase 3 intermediate-scale tests. Type II is also concave like Type I, but its width and height are reduced to lower construction costs. Type III has a concave wing only at one side, to accommodate the passage of ammo-loaded vehicles. Type IV has a simple plane face so that the ease of vehicle passage can maximized and the construction cost can be minimized.

For each barricade type, two tests were conducted with loading densities of 3.5 and 8.7 kg/m^3. The standoff distance from the exit to the barricades was one tunnel diameter (19.2 cm) for all tests. The test results showed that, for a constant NEW, the barricade performance in reducing the airblast hazard area decreased in the order of barricades Types I, II, III, and IV. The Type I barricade is recommended, since it reduced the total hazard area by a factor of two or more in almost all tests.

(3) Effect of Barricade Width and Height. It is important to design a barricade for the most economic construction. Measurements of debris distributions in the free-field in the ROK and U.S. Phase 3 intermediate-scale tests showed that the horizontal dispersion of the debris was

less than 10 degrees to the right and left of the extended tunnel centerline (Reference 25). This defined the required barricade size, for a given standoff distance, for debris-stopping purposes. It was also necessary to establish the optimum size needed for airblast control. Tests were therefore conducted in the Barricade Evaluation Study to determine how the effect of the barricade on the free-field airblast pressure varies as a function of its width and height. Since it is obvious that the relative effectiveness of the barricade size will change with its standoff distance, the width and height were interpreted as the horizonal and elevation angles, respectively, from the portal to the barricade (see Figure 3.29).

The external barricades used in these tests were Type V, which is shown in Figure 3.34. The Type V barricades are concave like Type II, but without the flat wingwalls. Barricades of six different widths were made by varying the degree of concavity, to provide horizontal angles (between the barricade edge and a line extending from the side wall of the tunnel exit) of 10, 15, 20, 25, 30, and 40.9 degrees. For the first series, the elevation angle was fixed at 20 degrees, and the standoff distance of one tunnel diameter was used. A loading density of 3.5 kg/m^3 was used for all tests. The results are listed in Table 3.4.

The dependence of the pressure coefficient, a_w, on the horizontal angle is plotted in Figure 3.35 and listed in Table 3.4. As shown in the figure, a_w increased as the horizontal angle increased. The value of a_w was given as a function of the horizontal angle, ϕ, by

$$a_w = 0.075 \ \phi + 2.12$$

The second series of tests investigated the effect of the elevation angle. The horizontal angle of the barricades was fixed at 20 degrees, and the elevation angle was varied from 8.6 to 23 degrees. The standoff distance and other details were the same as those in the horizontal angle tests. The results are listed in Table 3.5, and show that the value of a_w was relatively independent of the elevation angle.

(4) <u>Effect of Barricade Standoff Distance</u>. The barricade standoff distance is a critical factor. If the barricade is too far from the portal, its size must be large in order to intercept the

debris and airblast dispersion from the portal at the required elevation and horizontal angles. If it is too close, it will be difficult for vehicles to enter and exit the portal. Small-scale tests were conducted in this series to evaluate the performance of barricades at standoff distances of 1.0 to 3.0 tunnel diameters, using a Type I barricade and a loading density of 3.5 kg/m^3. Since the width and height of the barricade were fixed, the horizontal and elevation angles decreased as the standoff distance was increased.

As described earlier, changes in the barricade elevation angle did not significantly affect its performance. Therefore the changes in standoff distance could be represented by the corresponding values of the barricade horizontal angle. In Figure 3.36, the values of a_w as a function of different horizontal angles for a fixed standoff distance (of one tunnel diameter) are compared with those for varying standoff distances and their horizontal angles. Since the slopes of the two data curves are almost identical, the *change* in a_w as a function of the horizontal angle is more-or-less constant. The difference in the intercept values for the two curves is therefore attributed to the differences in barricade types--Type I for the variable standoffs, and Type V for the fixed standoff.

d. Reduction of Inhabited Building Distance. Prior to the UAST program, it was believed that portal barricades would reduce free-field airblast pressures only in the area immediately behind the barricade. In the ROK Phase 3 tests, Type I barricades were tested at 1/8-scale on the First Tunnel and the Fifth Tunnel, at a standoff distance of one tunnel diameter.

Figure 3.37 compares airblast pressure records at the tunnel portal and in the free-field at distances of 10 and 24 tunnel diameters along the extended tunnel centerline, from tests with and without barricades, for loading densities of 27 kg/m^3 in the First Tunnel. At a distance of 10 tunnel diameters, the peak pressure behind the barricade was less than 20 percent of that with no barricade. The entire waveform was reduced--not just the peak value. At a distance of 24 tunnel diameters, the peak pressure behind the barricade was still less than 30 percent of that with no barricade.

Figure 3.38 compares the peak pressure with and without barricades as measured on the First Tunnel test described above, and on a test in the Fifth Tunnel. The FifthTunnel was curved with a portal at each end--one with a barricade and one without. For both tests, it can be seen that the amount of pressure reduction provided by the barricade decreases somewhat with increasing distance from the portal. At IBD distance, however, the amount of peak pressure reduction is still dramatic--enough to reduce the IBD by more than a factor of two.

Figure 3.39 shows almost identical results from the small-scale tests performed in the Phase 4 Barrier Evaluation Study. The strong similarities between the 1/30-scale results and the 1/8-scale results confirms the theory that airblast effects can be modeled very accurately with small-scale experiments. On this basis, the findings of the Phase 4 study can be applied to large-scale barricades with a high degree of confidence.

e. Conclusions. Both the ROK and the U.S. Phase 3 tests showed that the dispersion angle for debris is less than ten degrees either side of the extended tunnel axis. Concave-type barricades with a horizontal angle of ten degrees (to each side of lines extended from the tunnel walls) and an elevation angle of ten degrees (above a line extended from the tunnel ceiling) will intercept any debris and, based on the Phase 4 results, will reduce the airblast IBD by at least a factor of two. This effectiveness factor applies to barricade standoff distances (measured from the portal to the plane of the forward edge of the barricade walls) of one to three tunnel diameters. The Type V barricade will be fully effective for both debris containment and airblast mitigation. However, Types I or II may be used, with no significant loss in effectiveness, if wingwalls are needed for structural stability.

3.5 PHASE 5: ENGINEERING DESIGN CONCEPTS

3.5.1 Purpose

The purpose of Phase 5 was to transfer the technologies developed by the UAST program to the U.S. and ROK explosives safety regulatory agencies (i.e., the U.S. DoD Explosives Safety Board (DDESB) and the ROK MND Explosives Safety Management Board (ESMB)) in a form

that could be used to officially establish new safety standards for underground ammunition storage, and that would allow construction of underground magazines by military users in a manner that would conform to those standards.

Three products were produced to accomplish this purpose. These were (a) a proposed revision of the current safety standards, to set forth the new QD's and other safety-related factors for underground storage that were established by the R&D effort, (b) a set of conceptual drawings and specifications for design and construction of underground magazines, and (c) a technical report to summarize the R&D results that formed the basis for the revisions of the safety standards and the new magazine designs. The revision of the safety standards and the drawings are discussed in the following sections, and are included as Appendices A and B, respectively. The third product--the technical summary report--is this document.

3.5.2 Revision of Safety Standards.

a. Previous Safety Standards. The basic purpose of the UAST R&D program was to show that significant reductions in required safety hazard distances (QD's) can be achieved by the use of underground magazines. At the beginning of the program, the QD requirements to be reduced were those stated in the 1984 edition of U.S. DoD 6055.9-STD, "Ammunition and Explosives Safety Standards". The standards given in that document are referred to here as the "previous" safety standards.

b. Current Safety Standards. In 1992, while Phase 2 of the UAST program was well underway, a new, 1992 edition of DoD 6055.9-STD was published by DDESB (Reference 1). Since the safety standards contained in that edition were those in existence at the completion of the UAST study, and were those which were revised on the basis of the study findings, the 1992 edition is referred to here as the "current" standards. The 1992 edition was used as the basis for measuring the amount of QD reduction achieved by the R&D program.

It is important to note that some changes were made in the QD's and other safety-related factors associated with underground magazines in the 1992 edition, after the beginning of the

UAST program. These included, for example, moderate reductions in IBD's for airblast and debris. The basis for the 1992 changes, however, included the 1988 Klotz Club Test at China Lake, CA, and other information that was available to the UAST technical and management staffs when the UAST study was initiated. The new information was, in fact, included in the original UAST R&D proposal, as indicators of the potential that was believed to exist for reducing QD's.

c. Revised Safety Standards. One of the two main objectives of Phase 5 of the UAST program was to provide recommendations for a revision of the current U.S. DoD safety standards that would reflect (and authorize) the use of the reduced QD values associated with underground magazines that were identified and demonstrated by the UAST program. A proposed revision of the current standards was prepared by the US/ROK technical teams, with the special assistance of the U.S. TAG, and submitted to the U.S. and ROK Program Managers for review and approval. The proposed revision was then submitted to the U.S. DDESB and the ROK ESMB for their review and approval in June 1996. The proposed revision was officially approved and accepted by the U.S. Board at their 22 August 1996 meeting, and by the ROK Board at their 3 December 1996 meeting.

The complete text of the revised portions of the safety standards, as approved by DDESB and ESMB, is given in Appendix A.

3.5.3 Definitive Design Drawings and Specifications.

Early in the UAST program, different design concepts, layouts, and hazard control features were considered by the ROK and U.S. technical teams. These were initially developed from existing underground facilities in other countries, and then modified on the basis of U.S. and ROK ammunition storage requirements, operational requirements, and other factors, such as potential benefits in survivability, security, visibility, etc. The designs were further refined as the tests and analyses of techniques for explosion hazard prediction and mitigation progressed, along with supporting studies related to construction and engineering, special requirements for underground storage and operations, cost-benefits analyses, etc.

Early in Phase 5, preliminary conceptual drawings and specifications for these designs, including specific hazard control features, were developed in accordance with the R&D findings and the proposed revisions to the safety standards. From this material, the U.S. Army Engineer Facility Engineering Services Center, at Huntsville, AL, produced a set of definitive design drawings.

It was decided that the preparation of "standard" design drawings, as used for ECM's and other above-ground magazines, would not be appropriate for the UAST program. This was based on the fact that detailed construction drawings for underground magazines will vary according to the topography, the structural geology, and other factors unique to each construction site. Definitive drawings, on the other hand, would provide alternative design concepts and descriptions of special features that would allow construction drawings to be tailored to specific sites. At the same time, the specifications accompanying the drawings would state the latitudes allowed in the actual construction drawings, for the facility to remain in conformance with the safety standards.

The definitive design drawings and specifications were submitted to the U.S. and R0K Program Managers in stages over a three-month period in late 1996. The final, complete set of drawings was submitted to and approved by the U.S. DDESB and the ROK ESMB in early December 1996.

A complete (but reduced) copy of the definitive design drawings is attached as Appendix B.

3.5.4 Supporting Studies.

a. Design and Operations Analysis of a Full-scale Facility. In the early stage of the UAST program, a multi-chamber design concept was proposed. Figure 3.40 shows the proposed design. With a few modifications, a facility of this general design was constructed to evaluate construction and storage operations problems, as well as the efficiency of the design itself. After completion of the facility, it was stocked with various types of ammunition to determine if long-

term (two years) storage in the underground environment would produce any deterioration or other problems with the stored munitions.

A study was conducted for the UAST program by the Korea Military Academy to perform the evaluations (Reference 41). The following findings were made:

- o The quality of the storage environment in the underground storage chambers was good (compared to storage in ECM's); a constant temperature of 15° C and a relative humidity of 55% were maintained in the storage chambers.
- o The utility costs (electricity) for operation and maintenance of the facility was feasible; the average cost was $31,000 per year (or $85/day).
- o Some air pollution occurred due to exhaust from gasoline or diesel engines operating in the facility.
- o Outside the storage chambers, condensation and dense fog occurred in the facility in summer, which deteriorated electric switches and similar items, and accelerated corrosion of materials.

Suggested design improvements included the following:

- o Electric overhead cranes are more desirable for loading/unloading ammunition trucks than are forklifts, in order to minimize the number of personnel and equipment required for operations.
- o The dimensions of the tunnels should be sufficient to accommodate two or more different types of material handling equipment (e.g., forklifts and overhead cranes).

- Ventilation capacities and air flow speeds should be increased for use of gasoline or diesel-powered equipment.
- Electrical switches and similar equipment should be moisture-sealed.

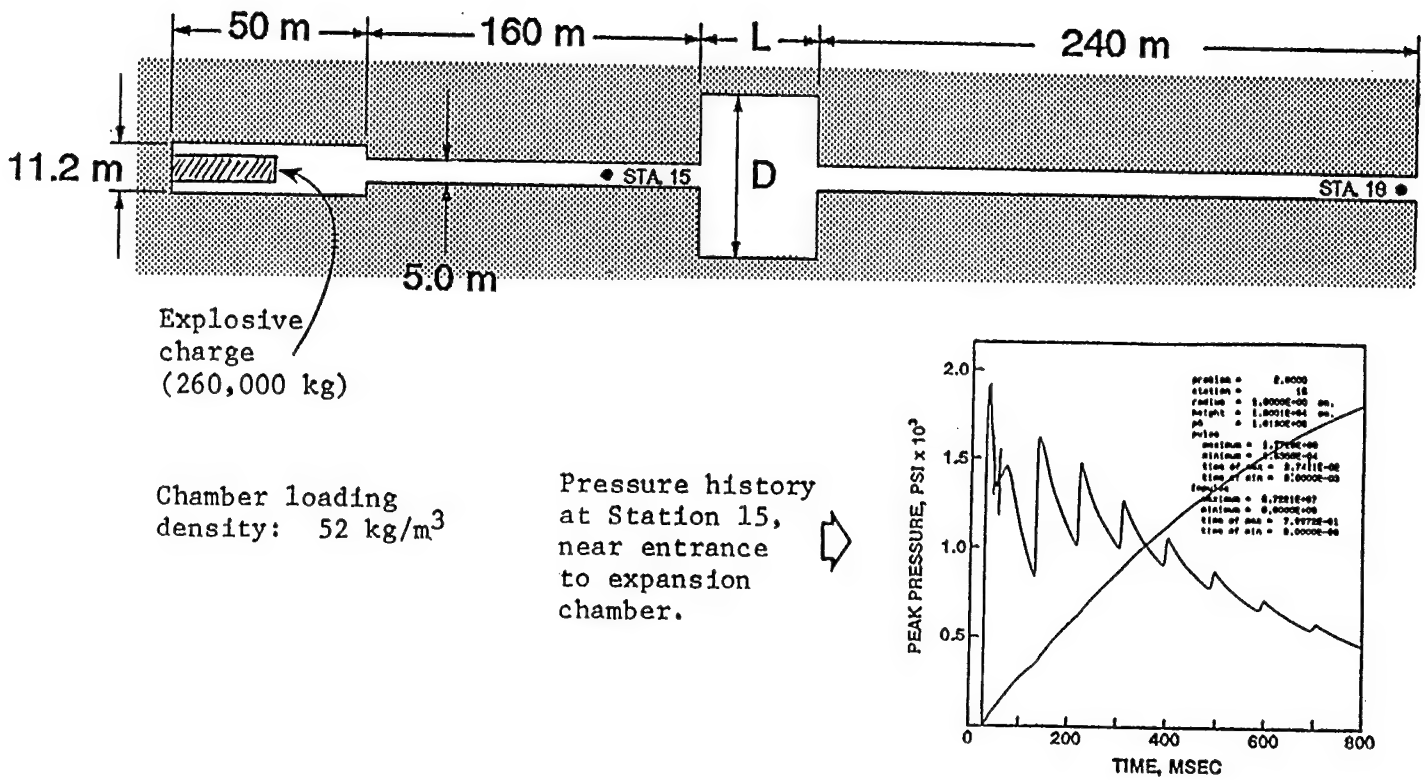


Figure 3.1 Magazine geometry and calculated pressure history for analysis of the effect of expansion chamber length (L) and diameter (d) on portal pressures, using a SHARC hydrocode model.

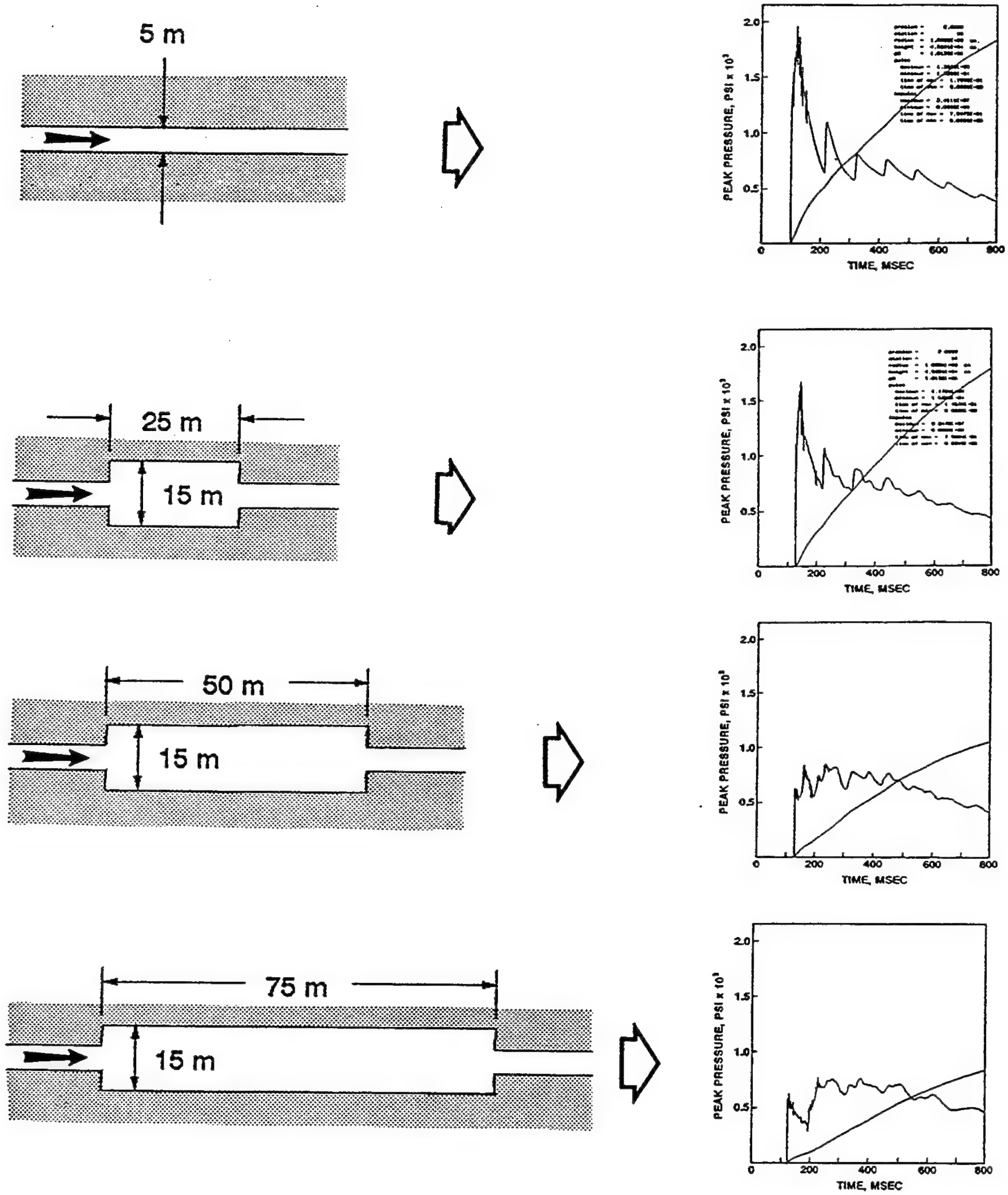


Figure 3.2 Pressure histories at Station 18 (near the tunnel portal) for expansion chambers of different lengths, as calculated from the SHARC hydrocode model shown in Figure 3.1.

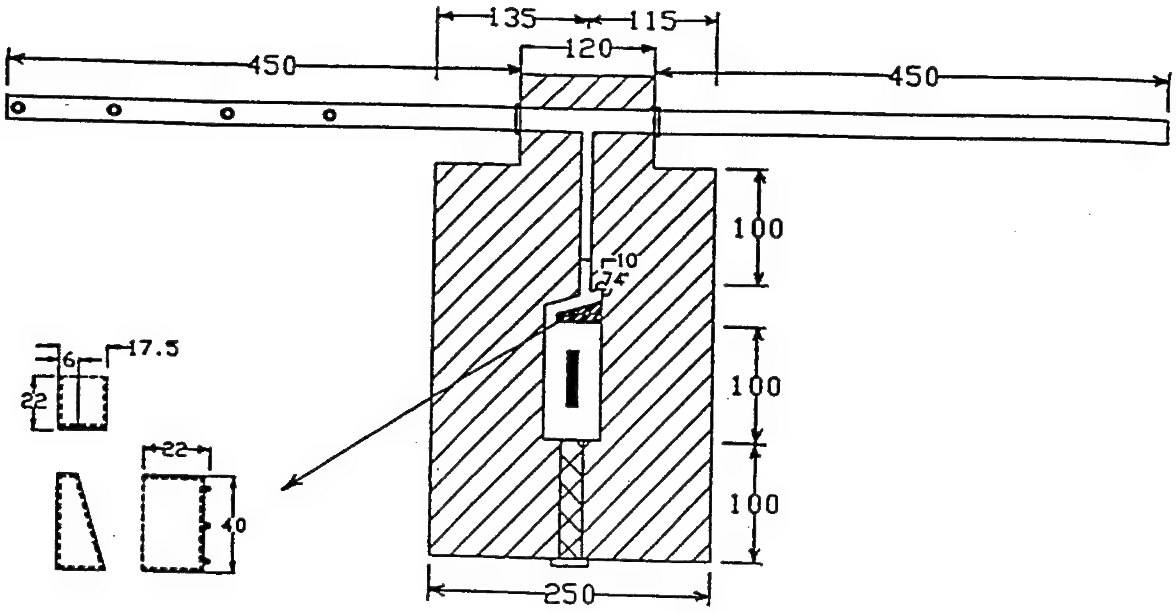


Figure 3.3a. Horizontal section view of an ROK small-scale magazine with a test closure block and a 4.6-kg C-4 charge in the storage chamber. Dimensions are in centimeters.

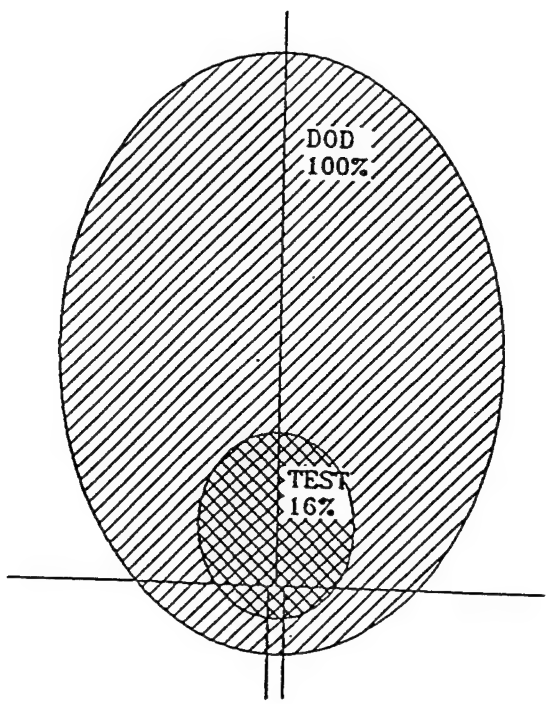
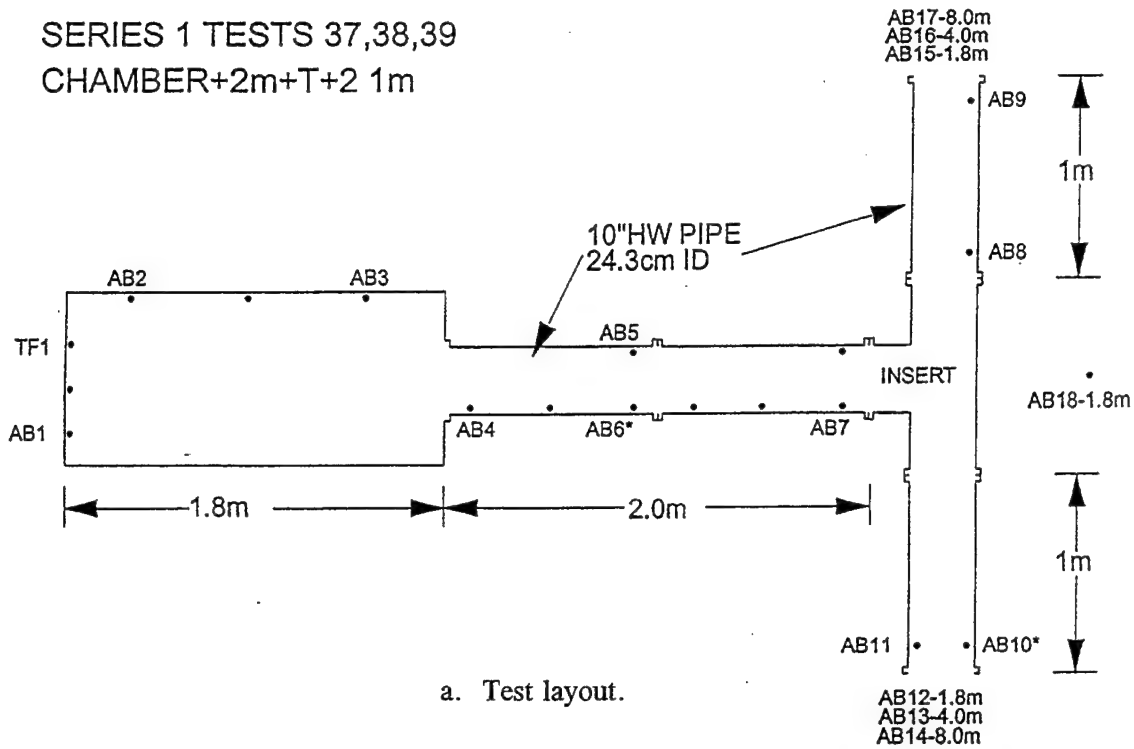
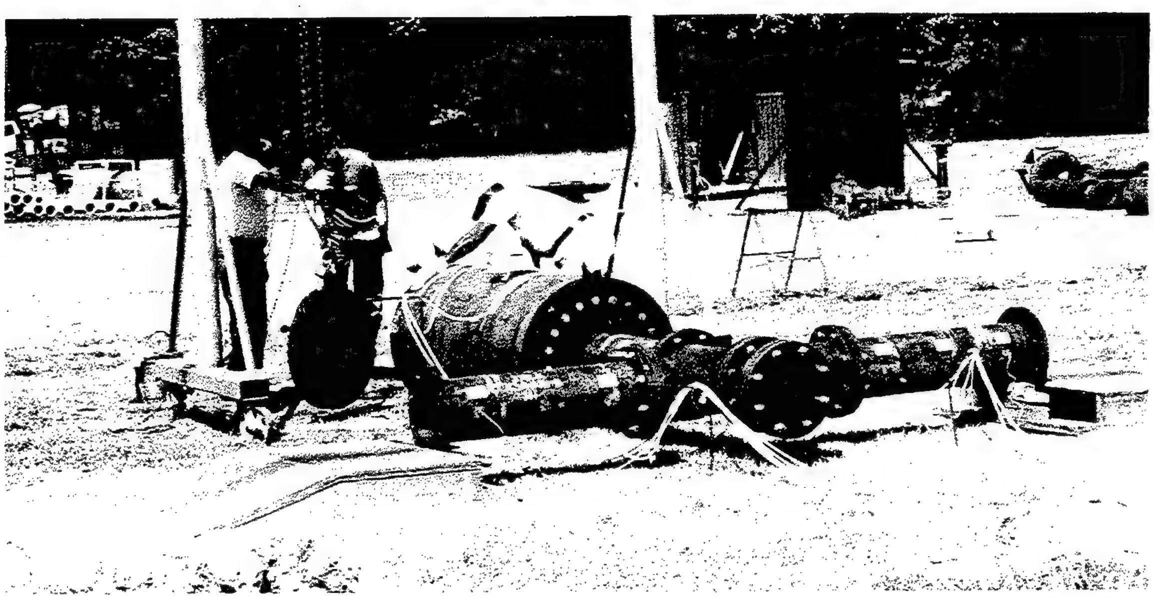


Figure 3.3b Airblast hazard area measured on ROK Phase 2 small-scale closure block experiment (TEST) compared to hazard area predicted by current DoD safety standards (DoD).



a. Test layout.



b. Assembly of tunnels and chamber for testing.

Figure 3.4 Set-up of 1/20-scale model magazine chamber and tunnels for investigation of "T" tunnel intersection effect on airblast, in U.S. Phase 2 program.

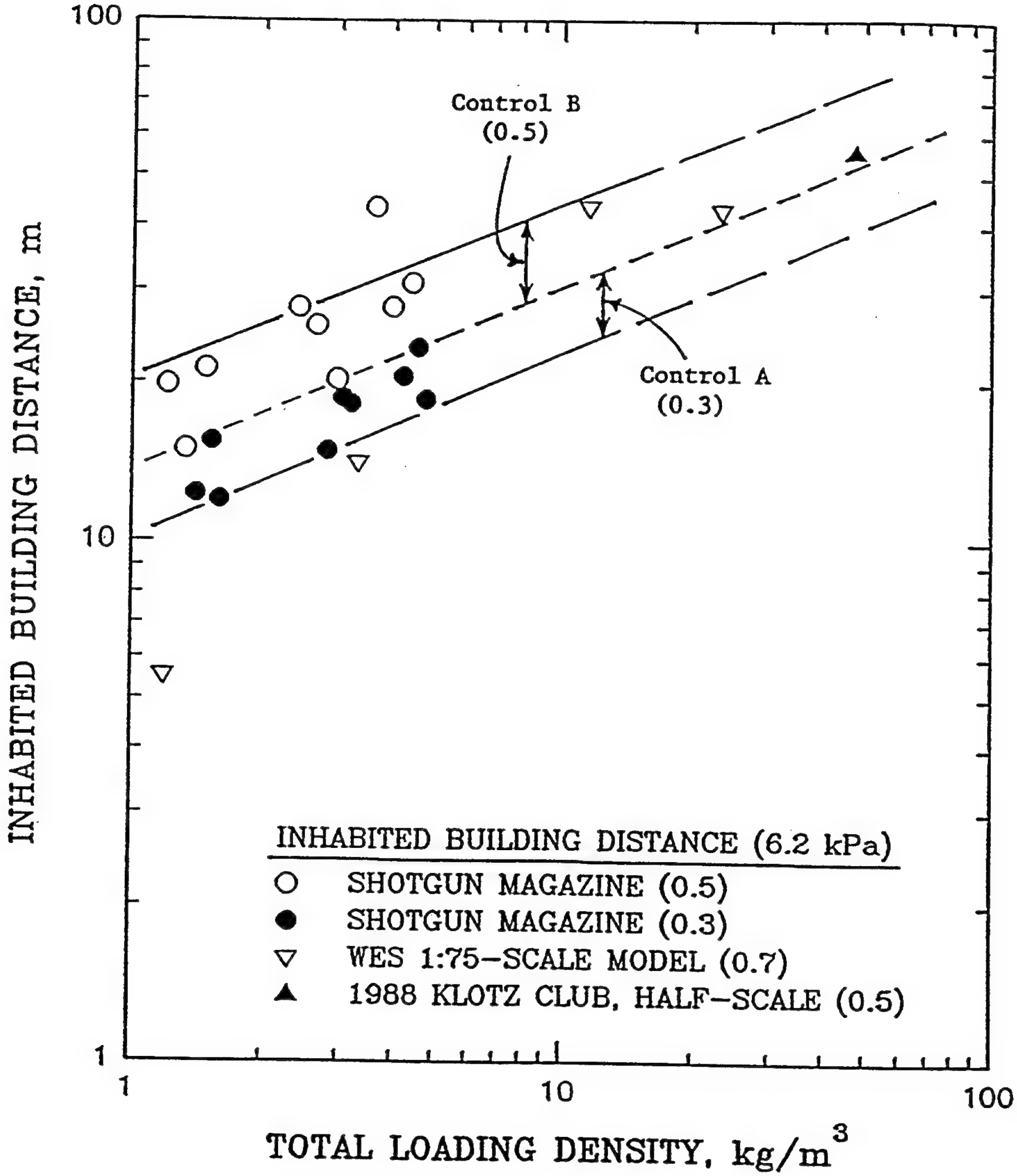


Figure 3.5 Inhabited Building Distances (QD_{IB}) values for U.S. Phase 2 tests of "shotgun"- type Control A and B magazines, compared to data from previous tests. Numbers in parenthesis are tunnel/chamber diameter ratios.

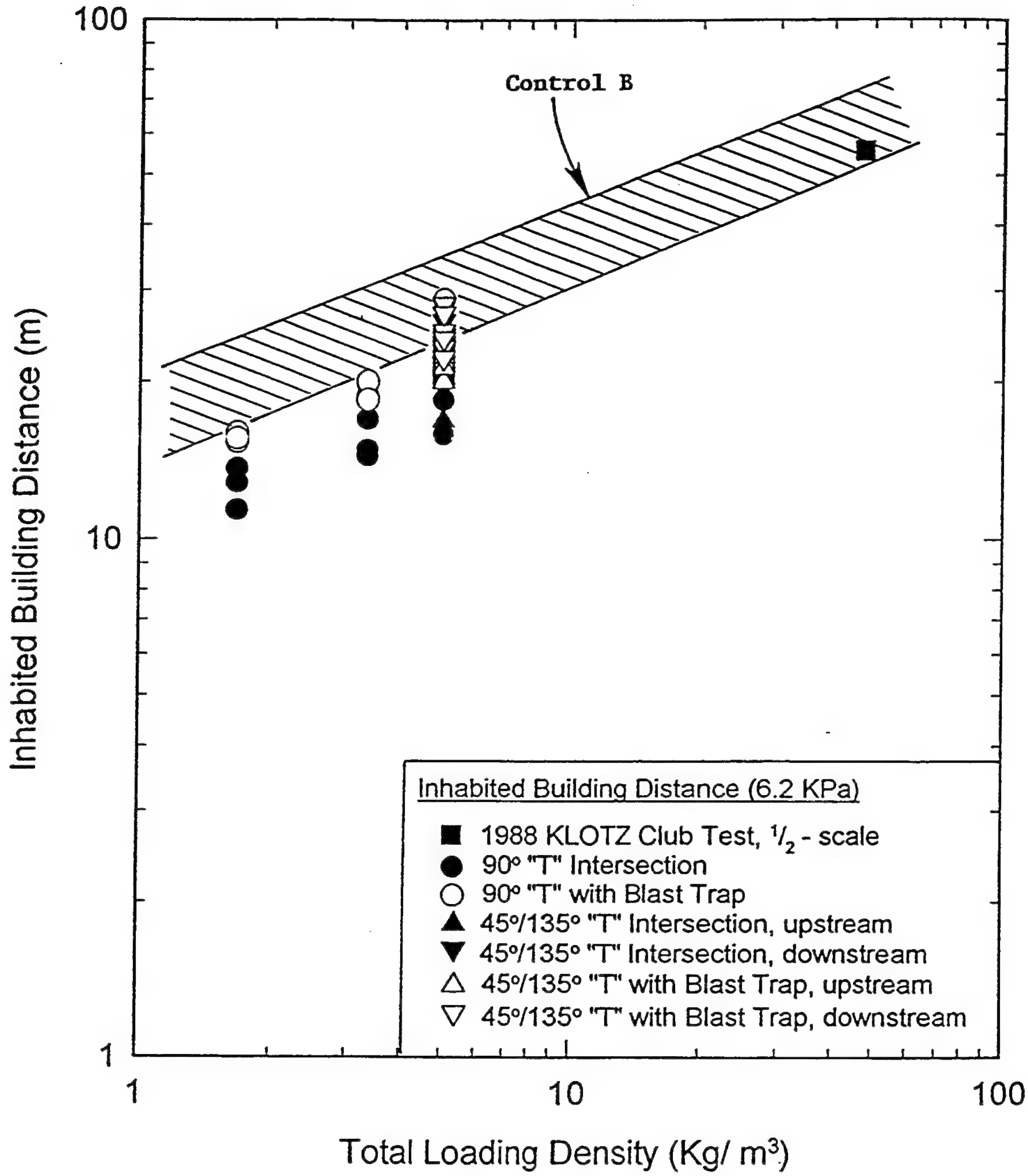
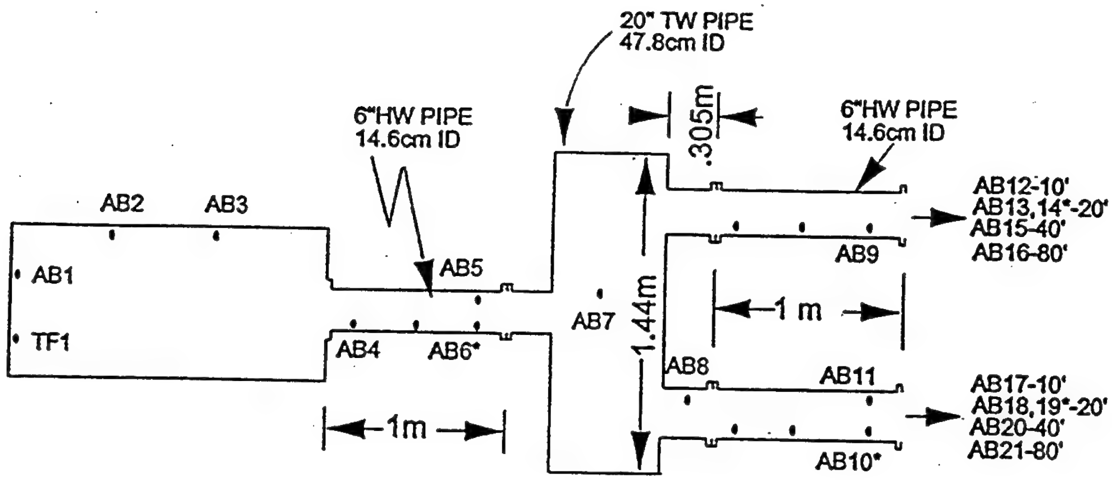
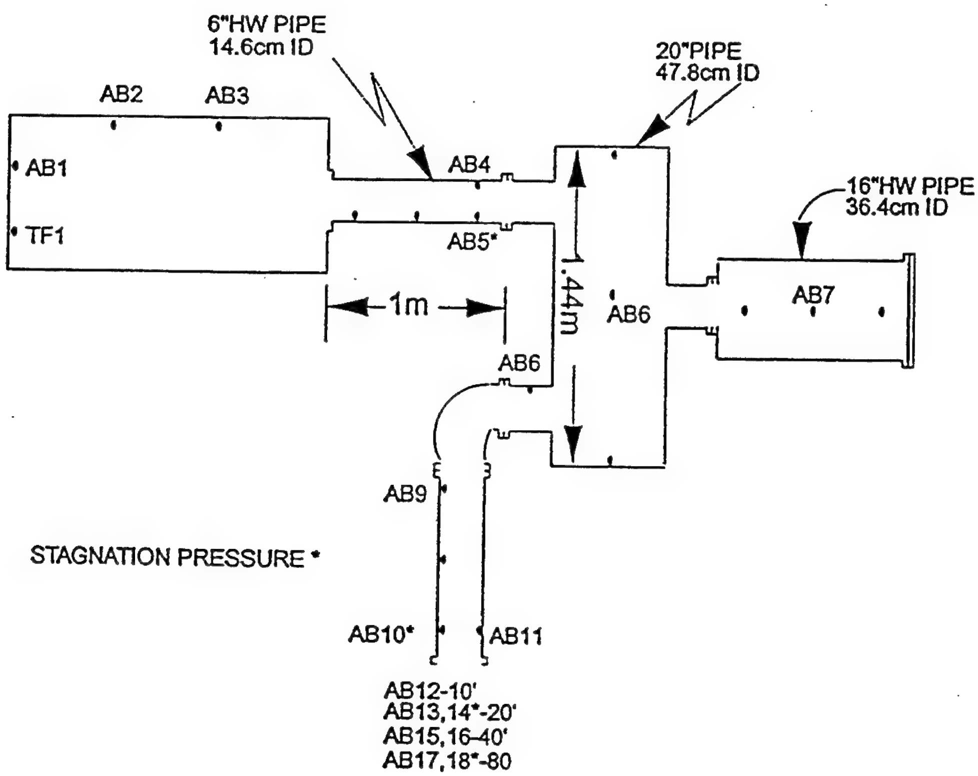


Figure 3.6 Inhabited Buildings distance (QD_{IB}) for tunnels with "T" intersections, with and without blast traps from U.S. Phase 2 tests. Results are Compared to QD's for Control Design B "shotgun" magazine models.



a. Transverse expansion chamber with two forward exits.



b. Transverse expansion chamber with one reverse exit and secondary chamber.

Figure 3.7 Test layouts for investigations of the effects of transverse (to main tunnel axis) expansion chambers on airblast, for U.S. Phase 2 test program.

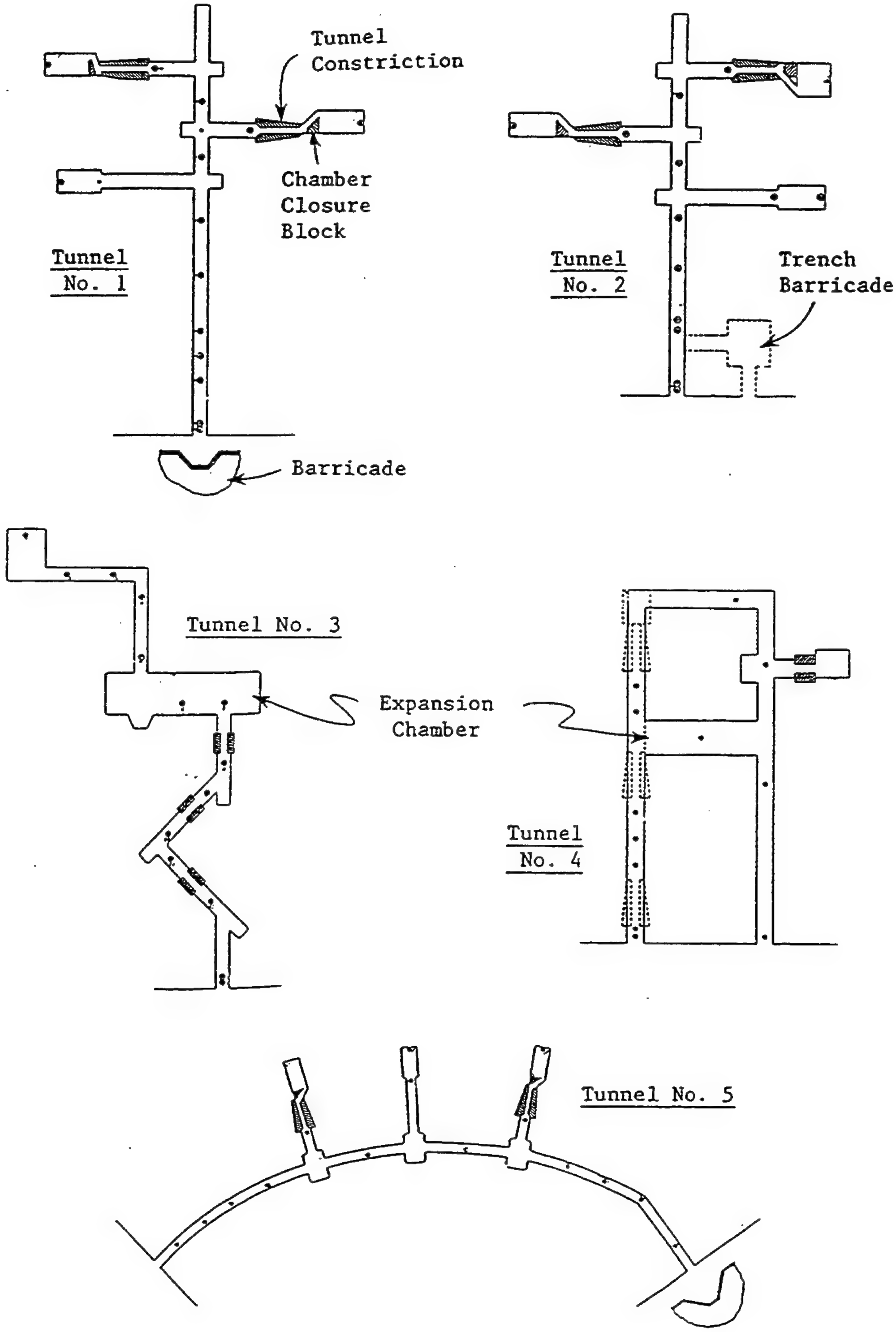


Figure 3.8 Layouts of 1/8-scale test tunnels and hazard control features for the ROK Phase 3 Intermediate-scale Test Program.

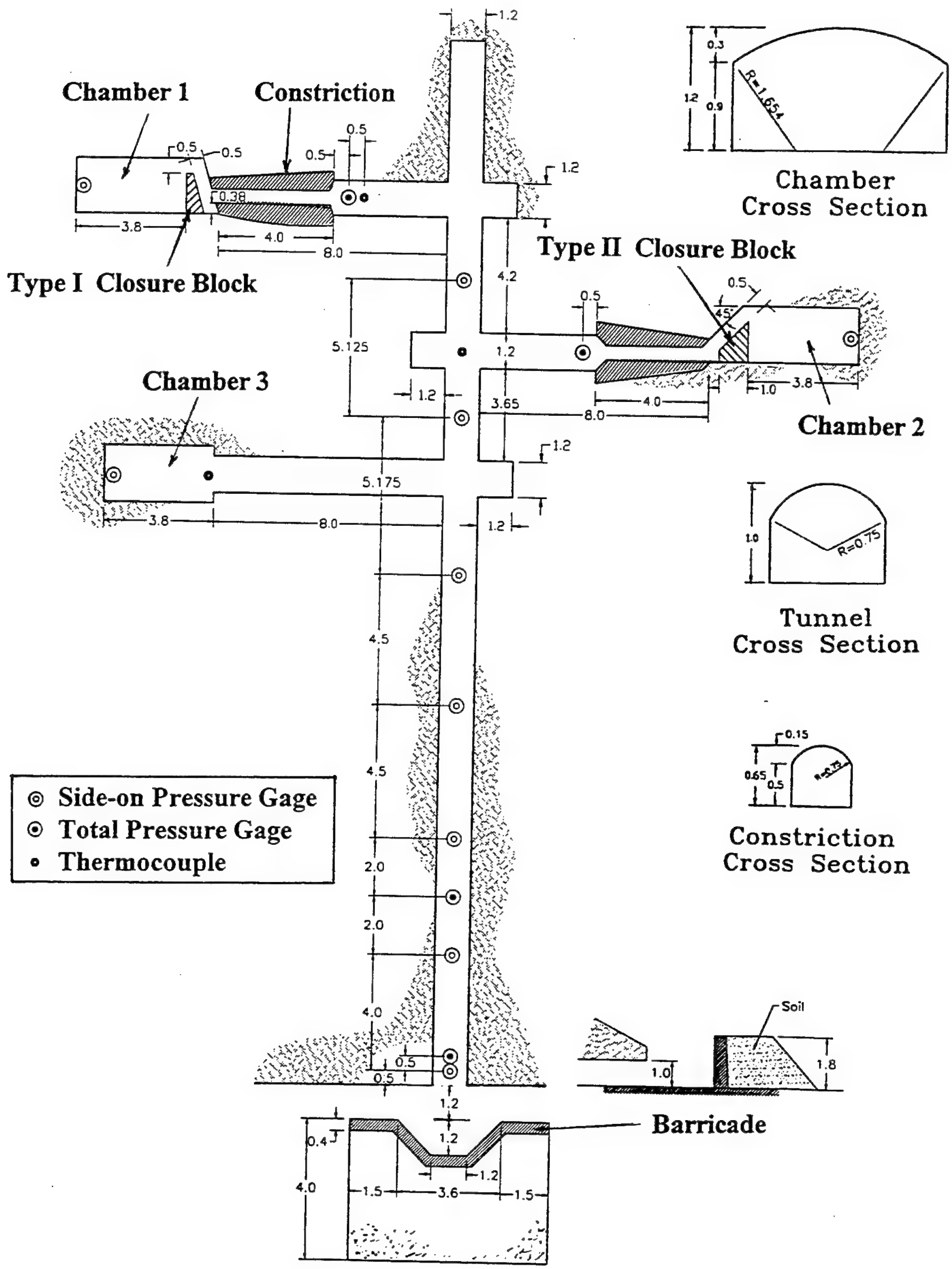
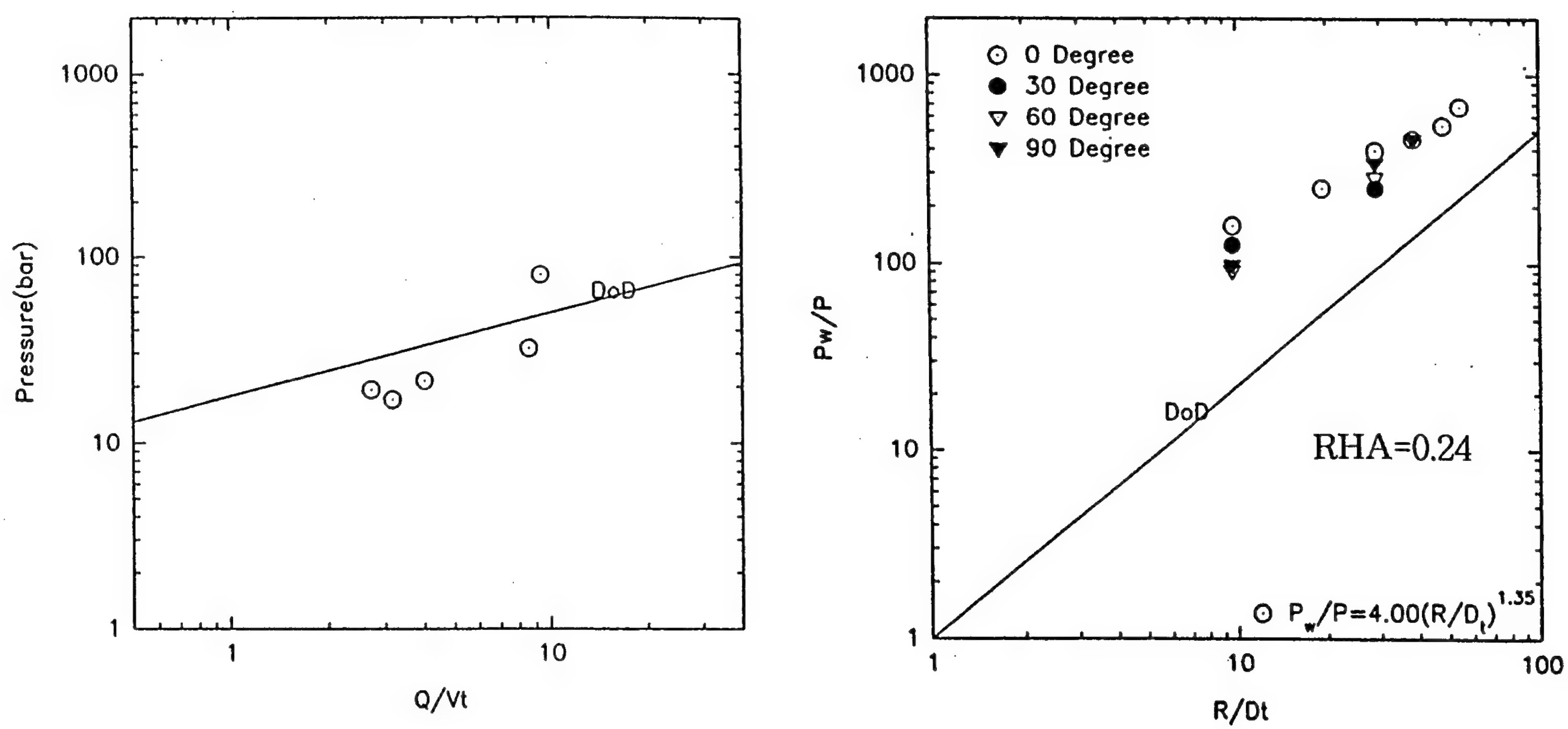


Figure 3.9 Airblast gage locations for tests in the First Tunnel of the ROK Phase 3 Intermediate-scale Test Program. All dimensions are in meters.



a. Tunnel pressures

b. Free-field (external) pressures

Figure 3.10 Airblast peak pressures predicted by current DoD safety standards (solid curve) compared to measured pressures (a) in the tunnel and (b) beyond the portal, for ROK Phase 3 test with a portal barricade (First tunnel, Chamber 3, Test 4). Q is the net explosive weight; V_t is the total tunnel volume up to the point of measurement; P_w is the portal pressure; D_t is the portal diameter; and P is the measured pressure at a distance R from the portal.

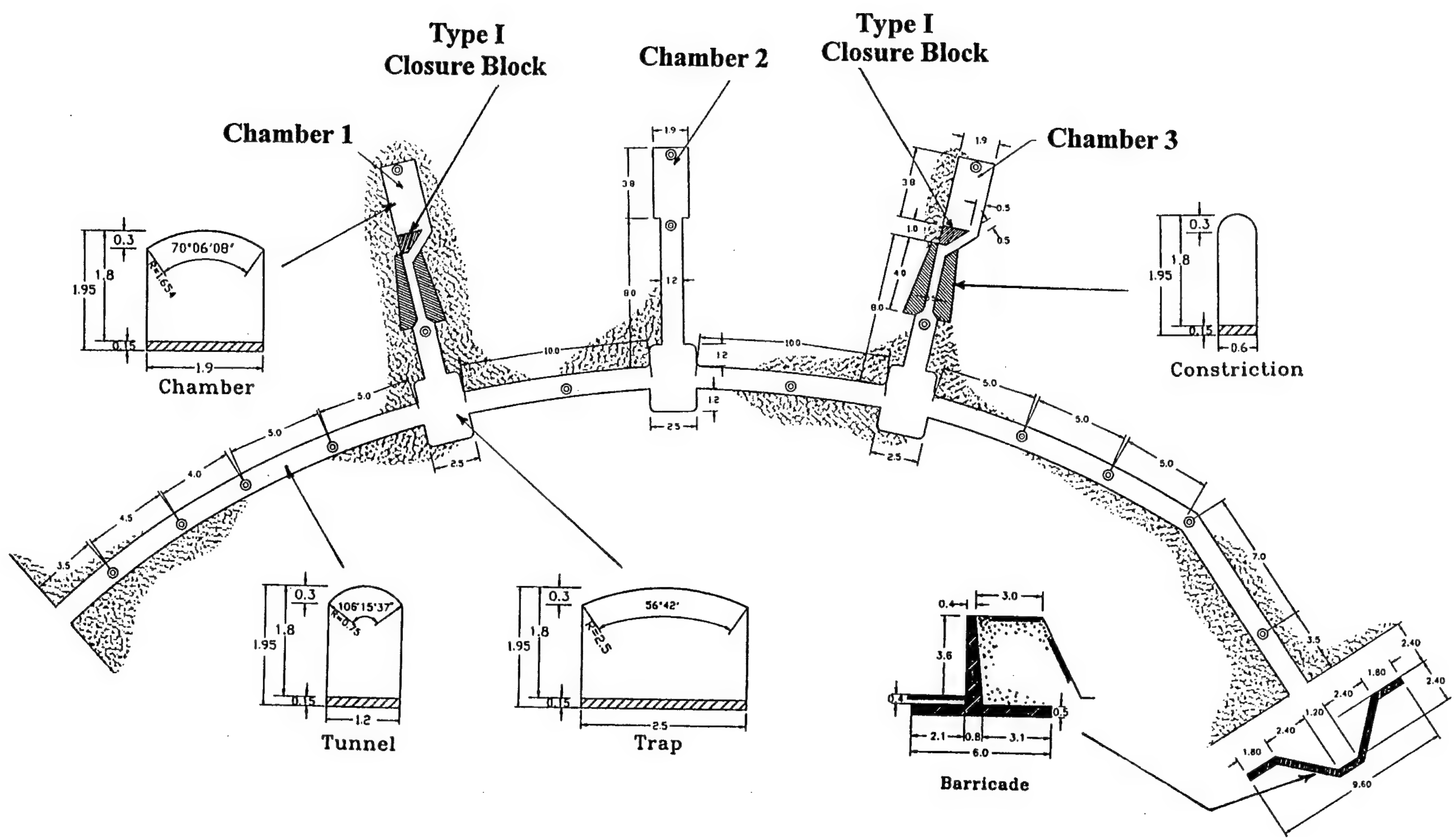


Figure 3.11 Test layout, with closure blocks, barricade, and airblast gage locations in the Fifth Tunnel of the ROK Phase 3 program. All dimensions are in meters.

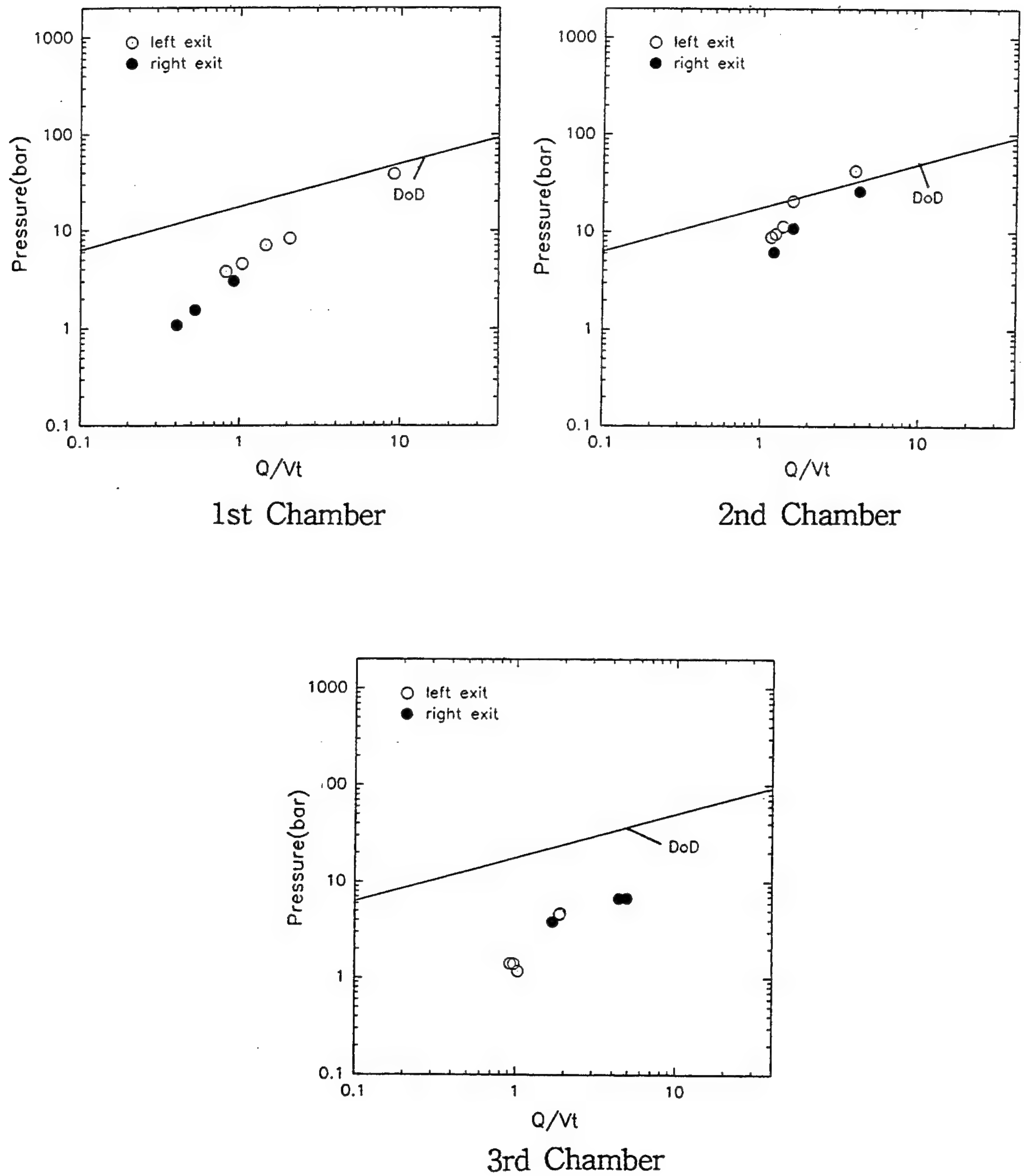
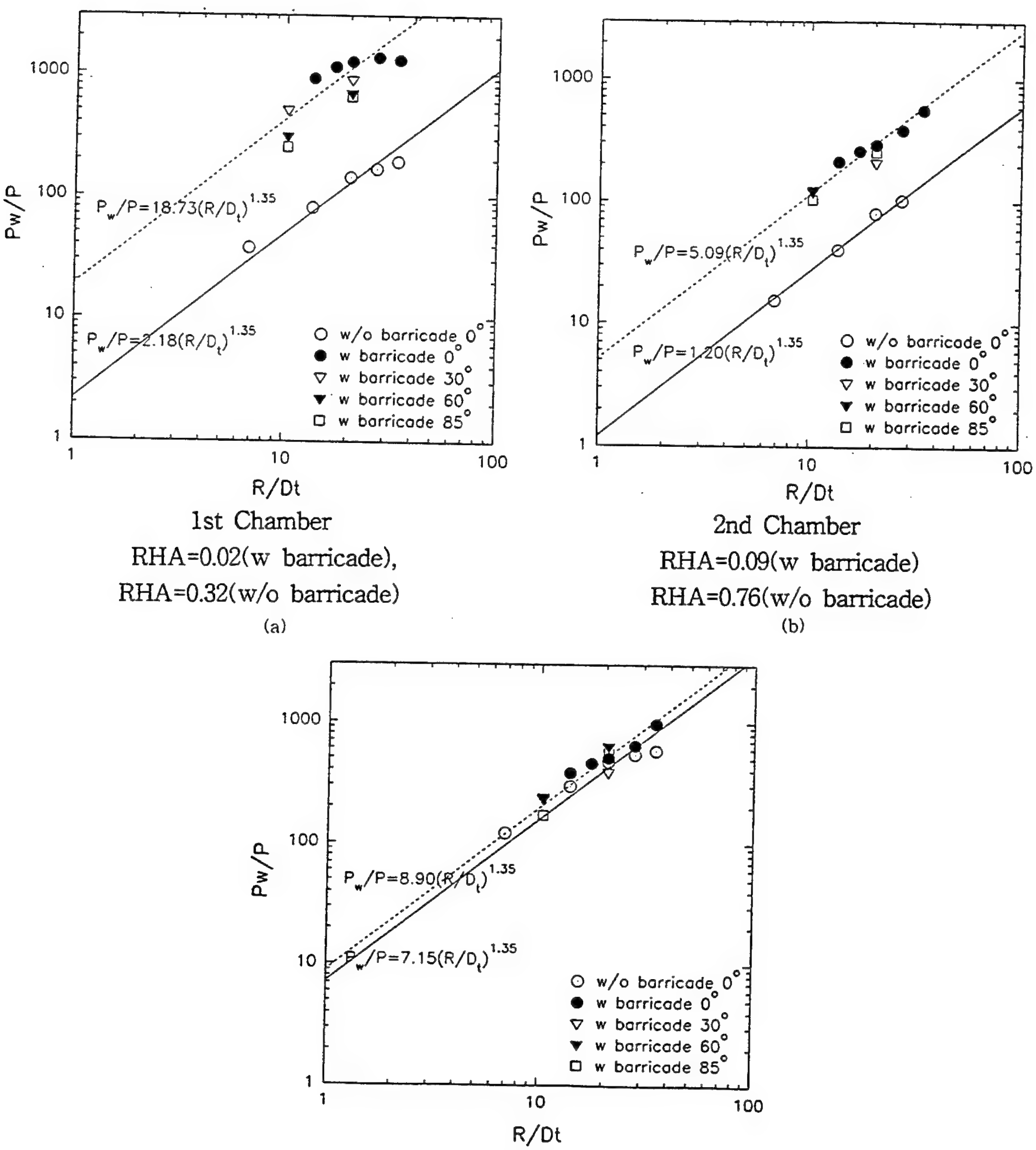


Figure 3.12 Internal peak pressures versus distance (expressed as Net Explosive Weight (Q) divided by tunnel volume (V_t) between test chamber and measurement point) for tests in Chambers 1 and 3 (with closure blocks) and Chamber 2 (no closure block) of Fifth Tunnel. Curve represents pressures predicted by current DoD safety standards.



1st Chamber
RHA=0.02(w barricade),
RHA=0.32(w/o barricade)
(a)

2nd Chamber
RHA=0.09(w barricade)
RHA=0.76(w/o barricade)
(b)

3rd Chamber
RHA=0.07(w barricade)
RHA=0.05(w/o barricade)

Figure 3.13 Free-field peak pressures (P) at range R, expressed as a function of portal pressure (P_w), for tests in Chambers 1-3 of the Fifth Tunnel. D_t is tunnel diameter. Data symbols indicate direction (azimuth) from portal, with 0° as the extended tunnel centerline.

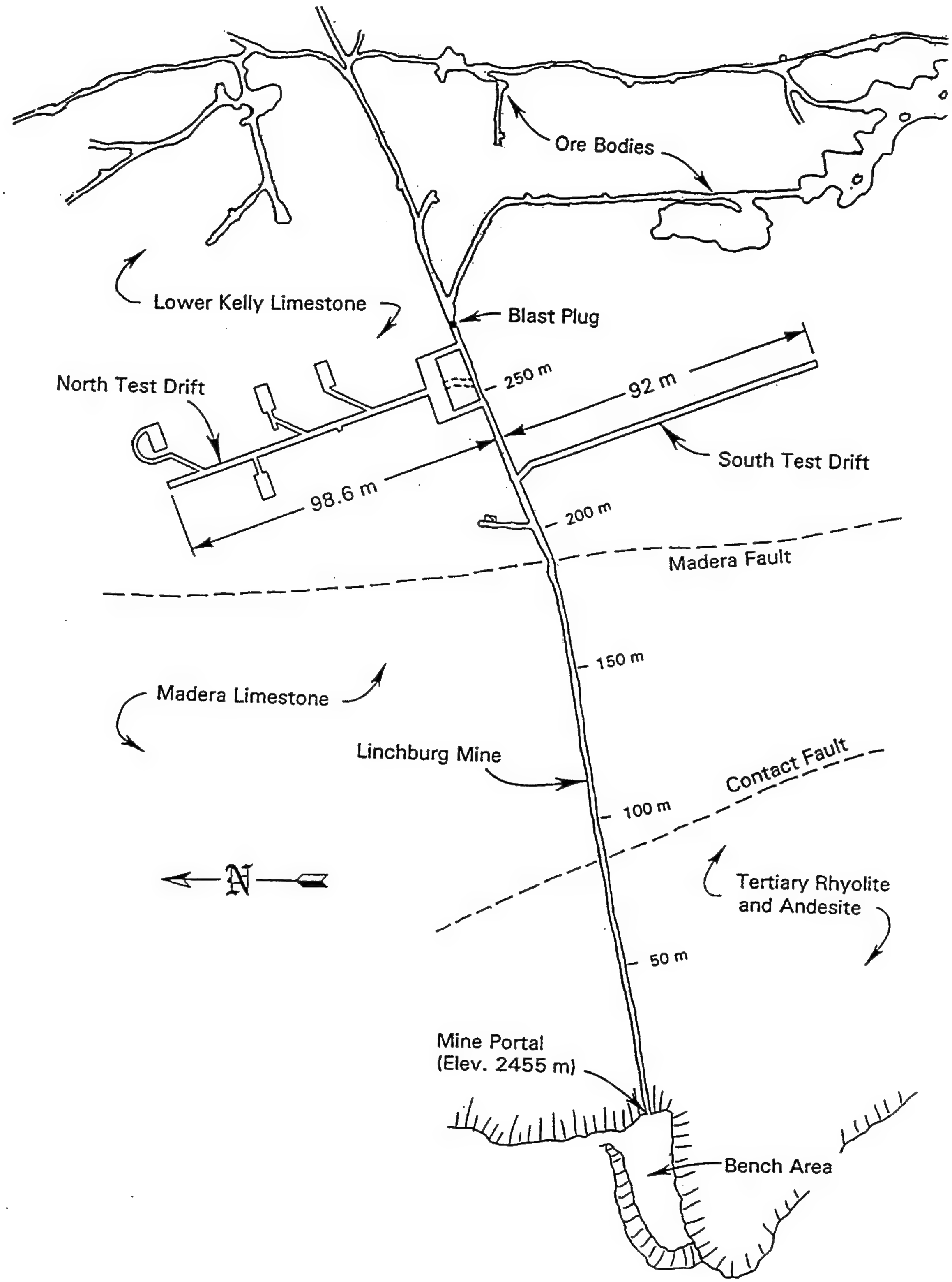


Figure 3.14 Layout of the Linchburg Mine test area for the U.S. Phase 3 Intermediate-scale Test Program.

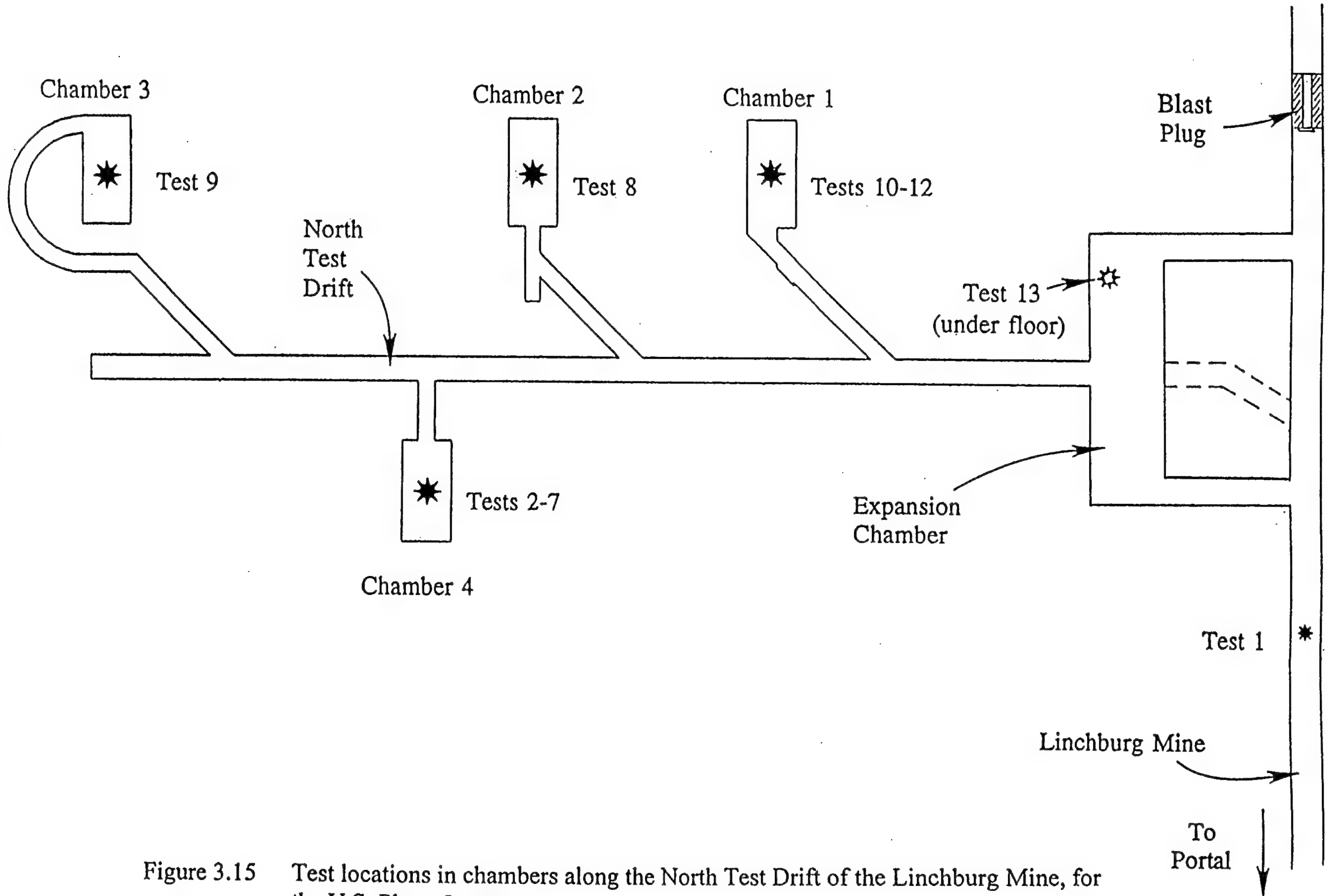


Figure 3.15 Test locations in chambers along the North Test Drift of the Linchburg Mine, for the U.S. Phase 3 tests.

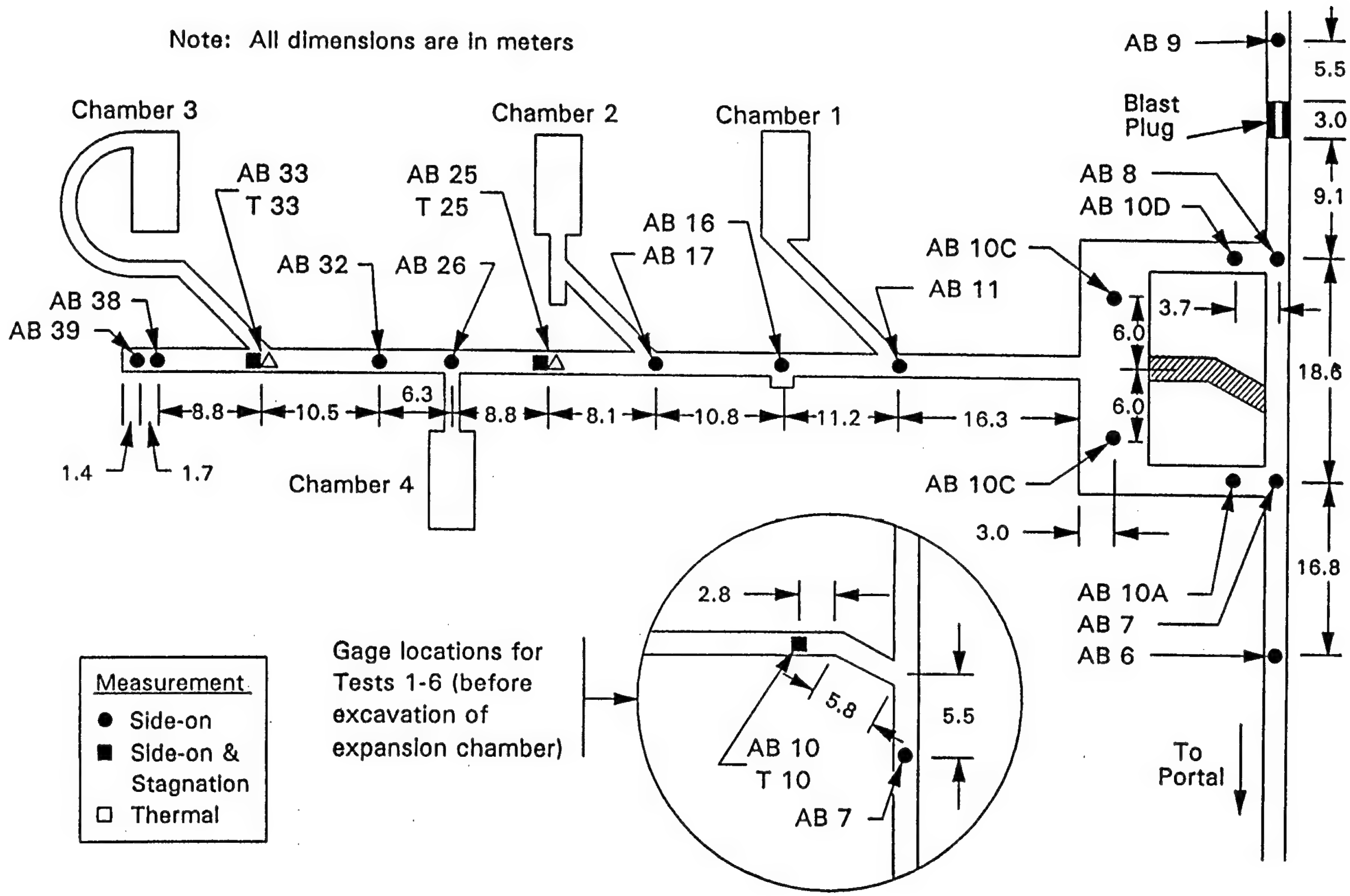


Figure 3.16 Airblast gage locations in the North Test Drift area of the Linchburg Mine.

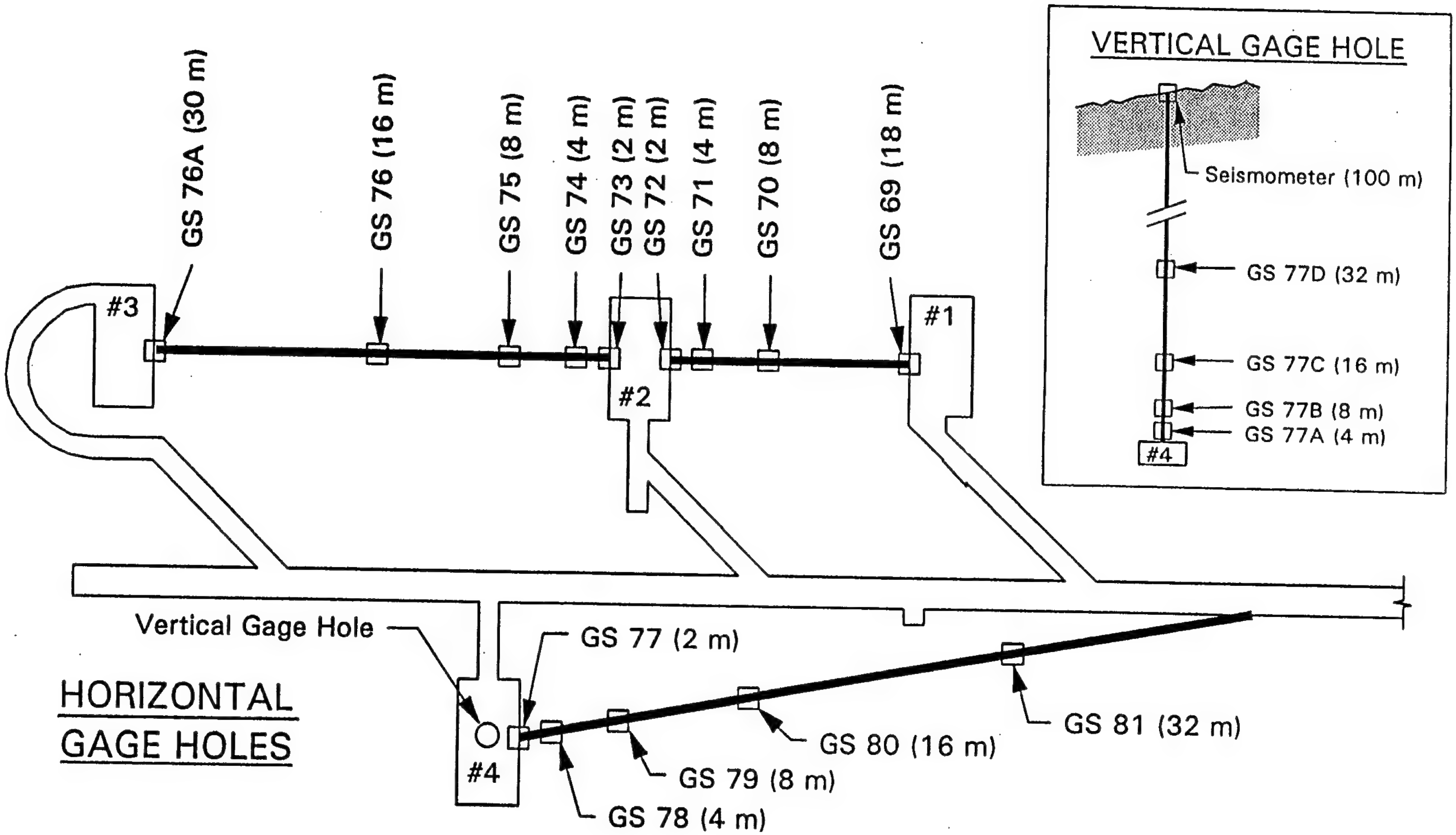


Figure 3.17 Ground shock instrumentation layout for U.S. intermediate-scale tests. All gage holes were 200 mm in diameter and stemmed with rock matching grout. Gage distances (in parentheses) are measured from center of test chambers.

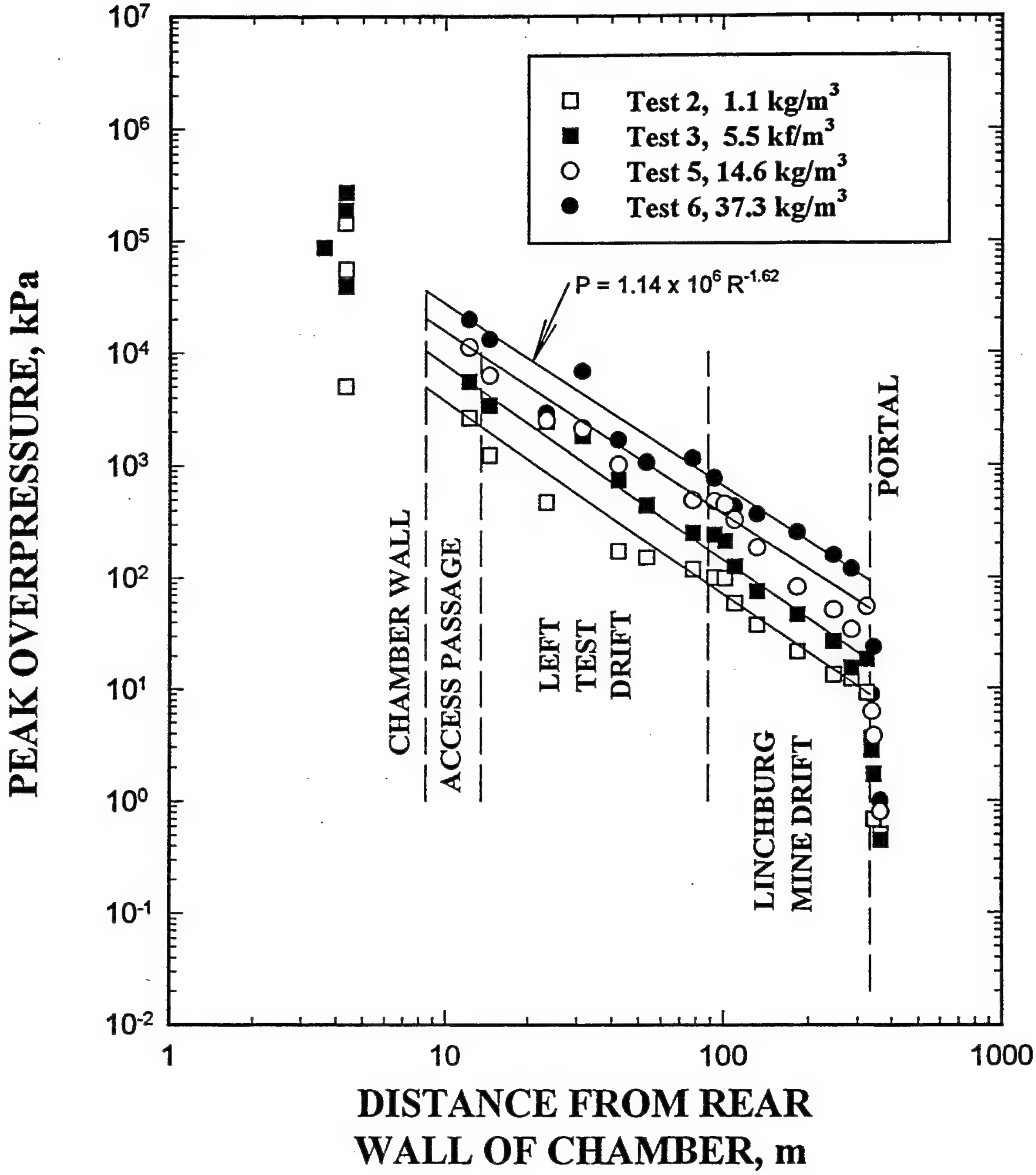


Figure 3.18 Peak side-on airblast overpressure as a function of distance along main blast flow path to portal, from Tests 2-6 in Chamber 4. Curves show data trends for the four different chamber loading densities.

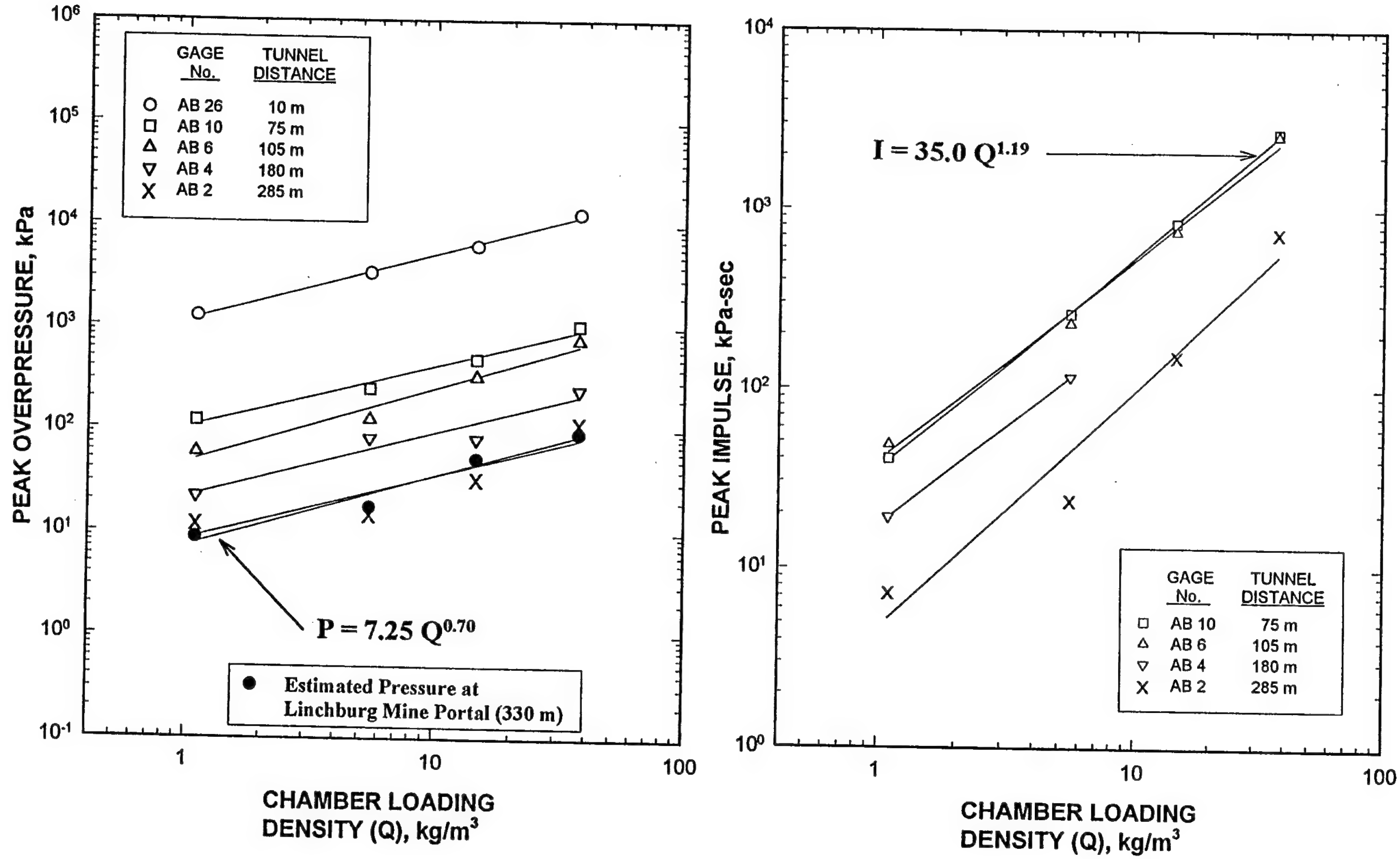


Figure 3.19 Peak airblast overpressure and impulse along main blast flow path as a function of chamber loading density for Tests 2-6 in Chamber 4.

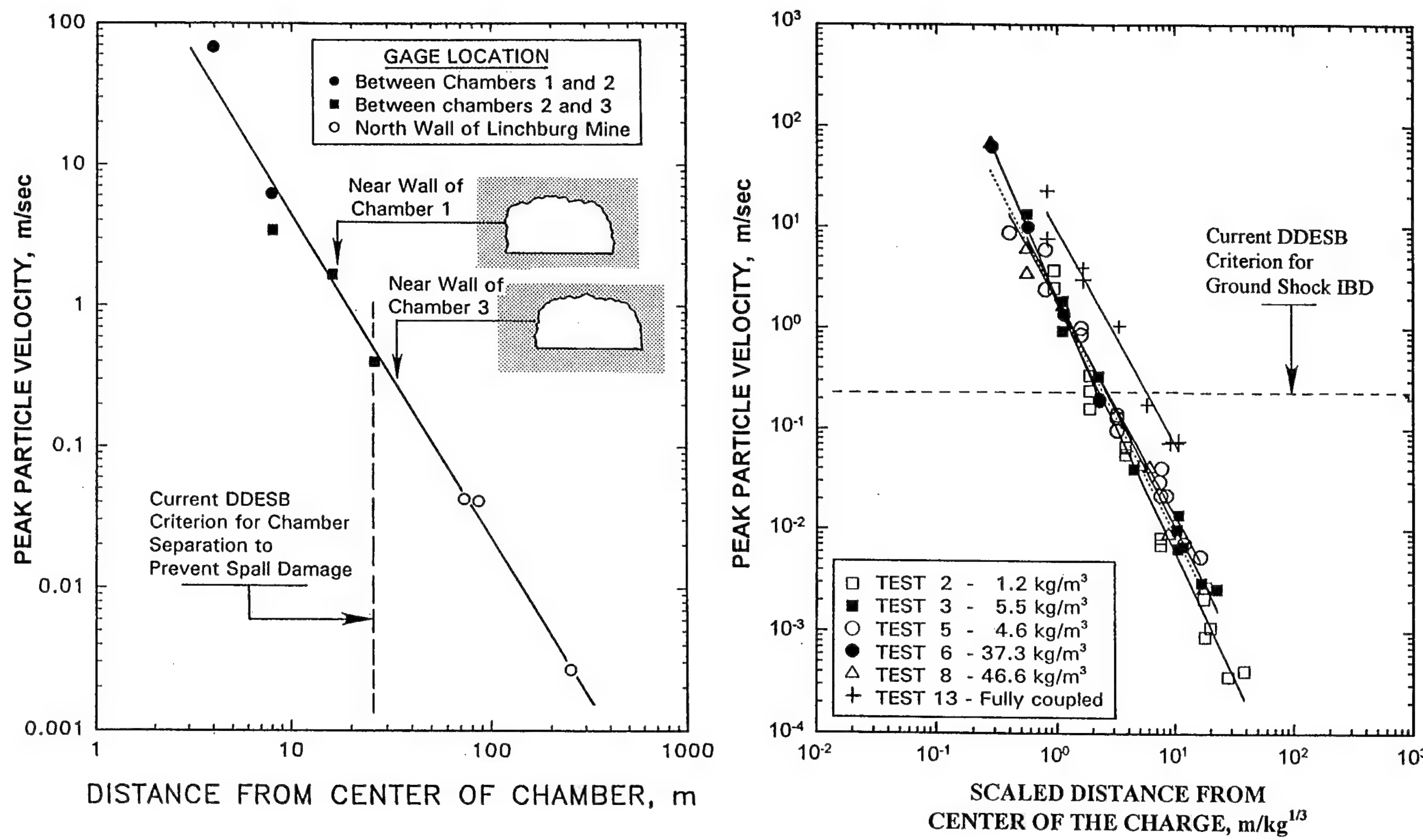


Figure 3.20 Measured peak ground shock particle velocity as a function of distance from Test 8 in Chamber 2 (left) and scaled distance from tests of different loading densities, from U.S. Phase 3 tests (right).

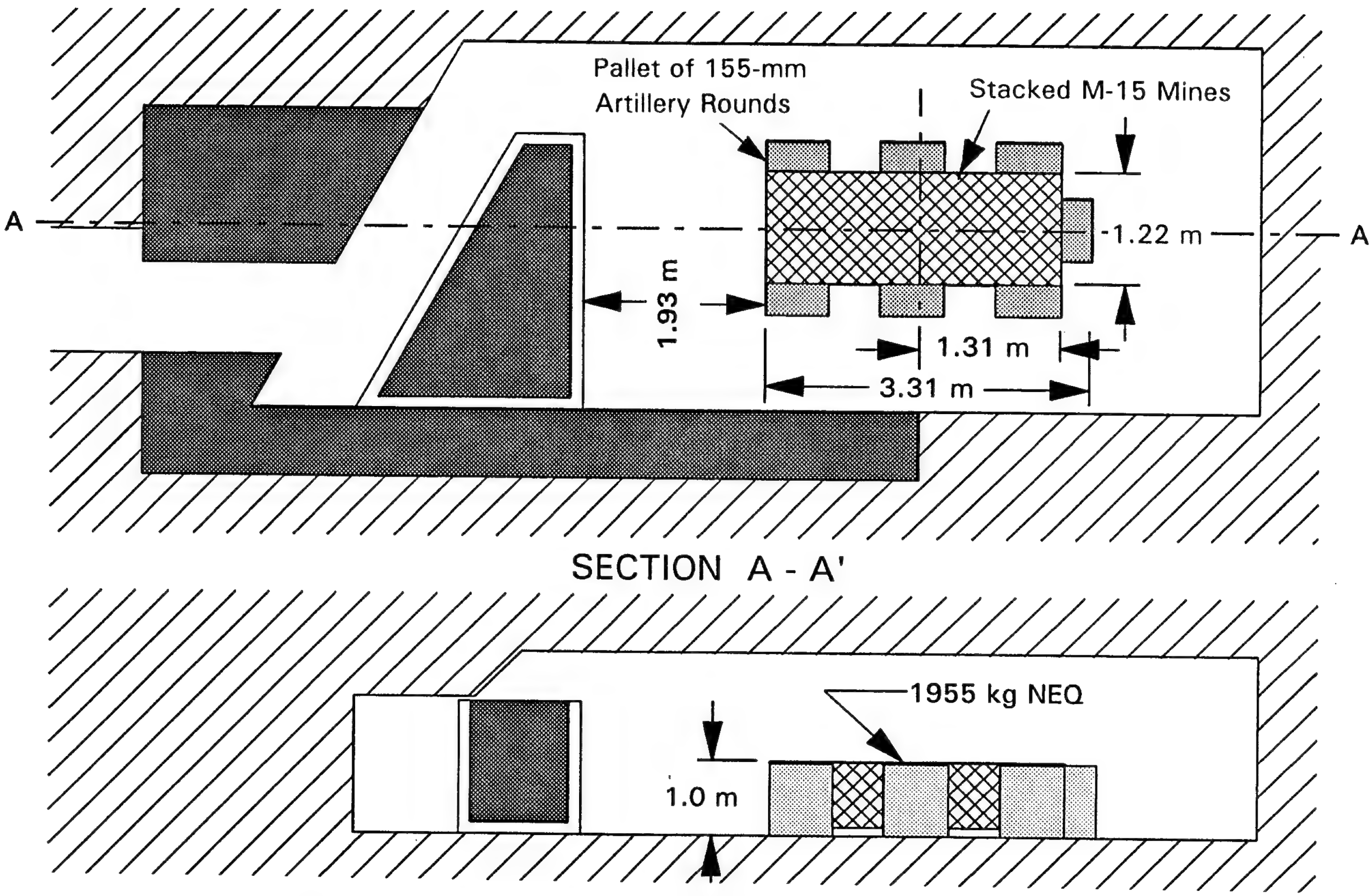


Figure 3.21 Plan and side elevation views of Chamber 2 modifications, closure block position, and explosive charge for Phase 4 Validation Test.

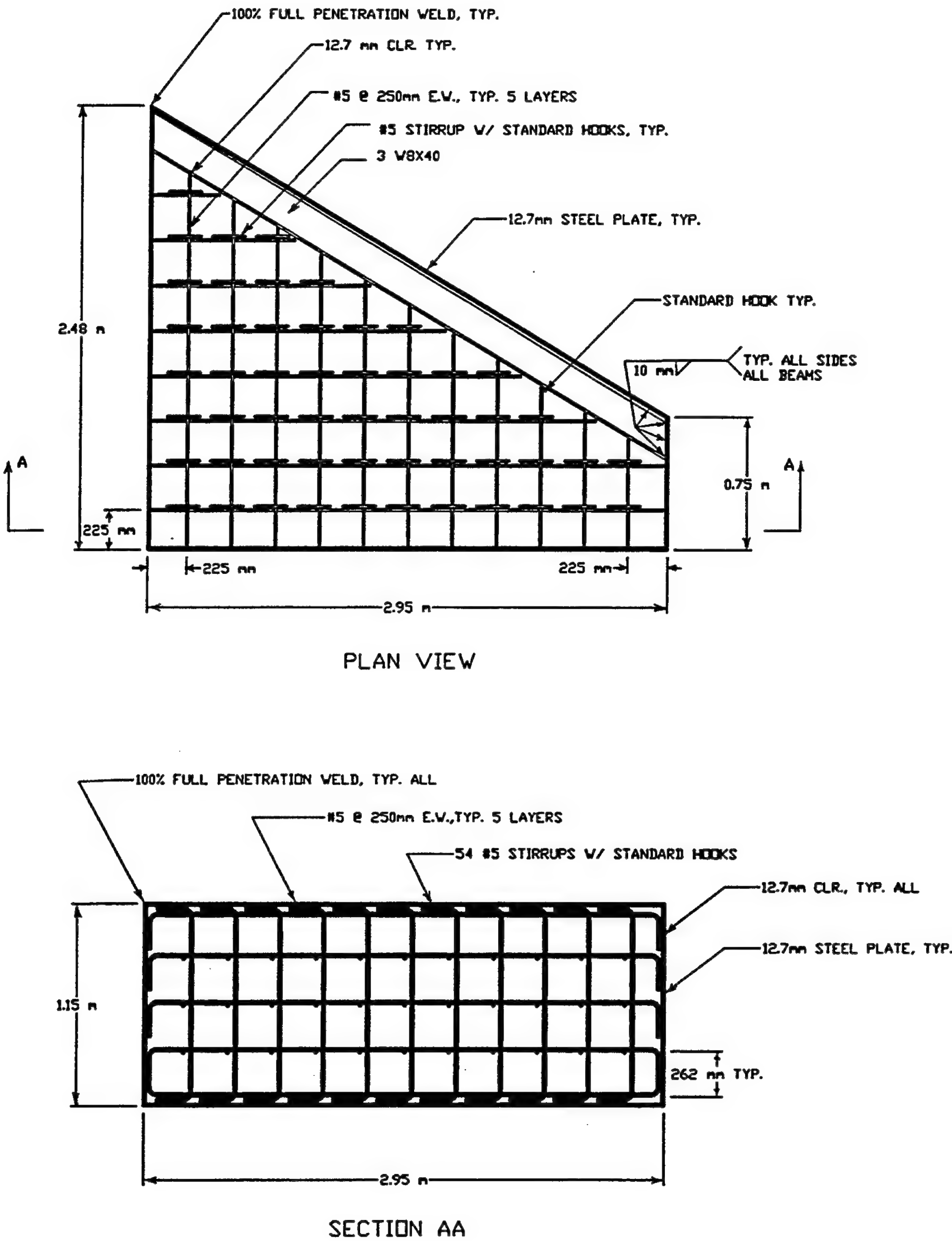


Figure 3.22 Design of the Magae closure block used in the Phase 4 Validation Test.

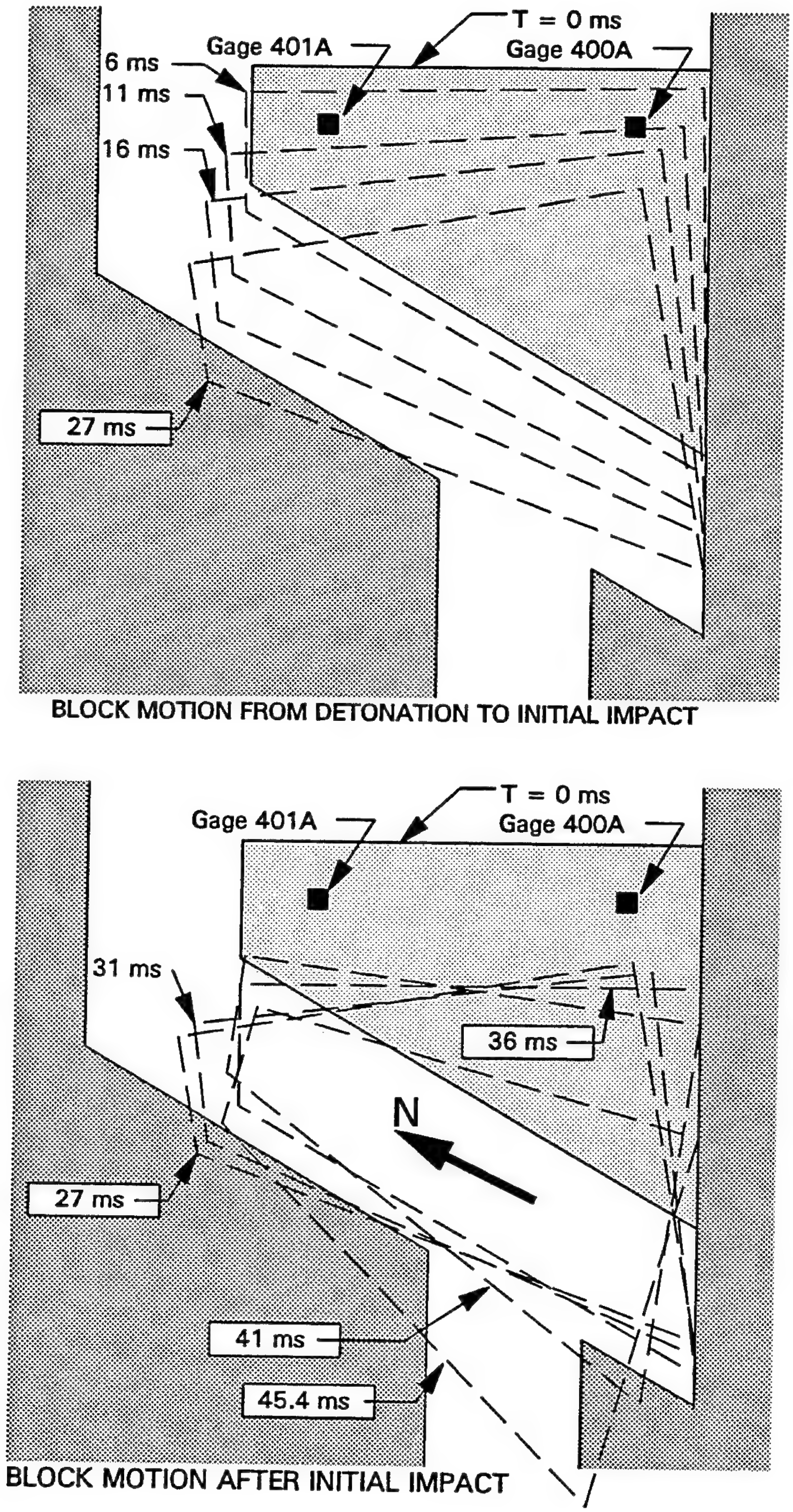


Figure 3.23 Position of closure block at selected time increments after detonation, as derived from displacement-time histories generated by closure block instrumentation (Gages 400A and 401A).

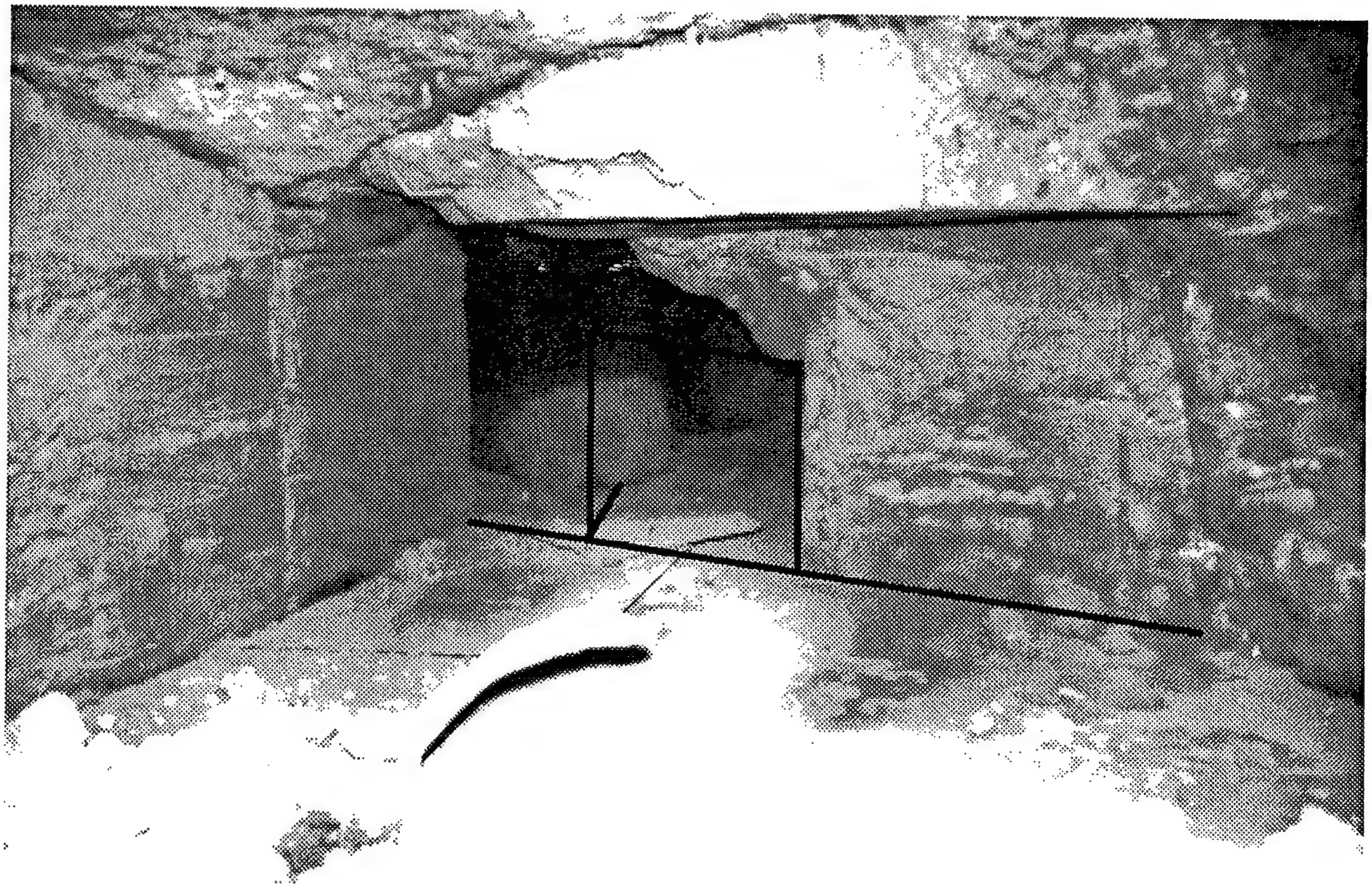
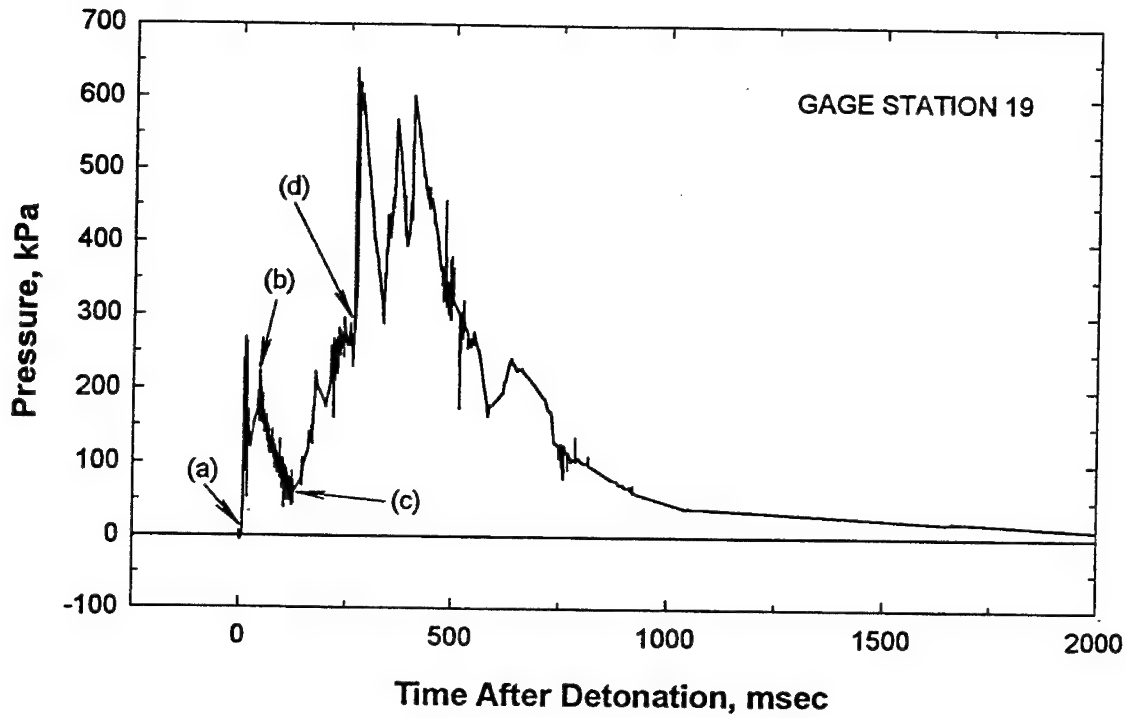


Figure 3.24 Photograph showing the post-test condition of the west wall of the test chamber after impact of the closure block. Lines drawn on the picture show original location of the wall and egress passage from the test chamber to the North Test Drill.



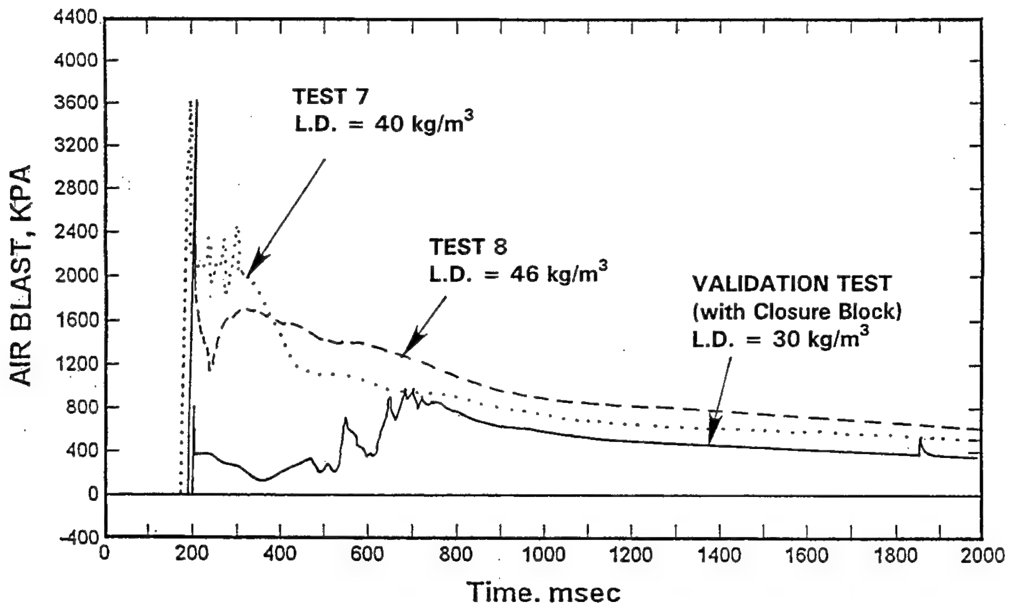
(a) Shock Arrival at Gage 19 (7.81 msec)

(b) Block Closure, Pressure Choked Off

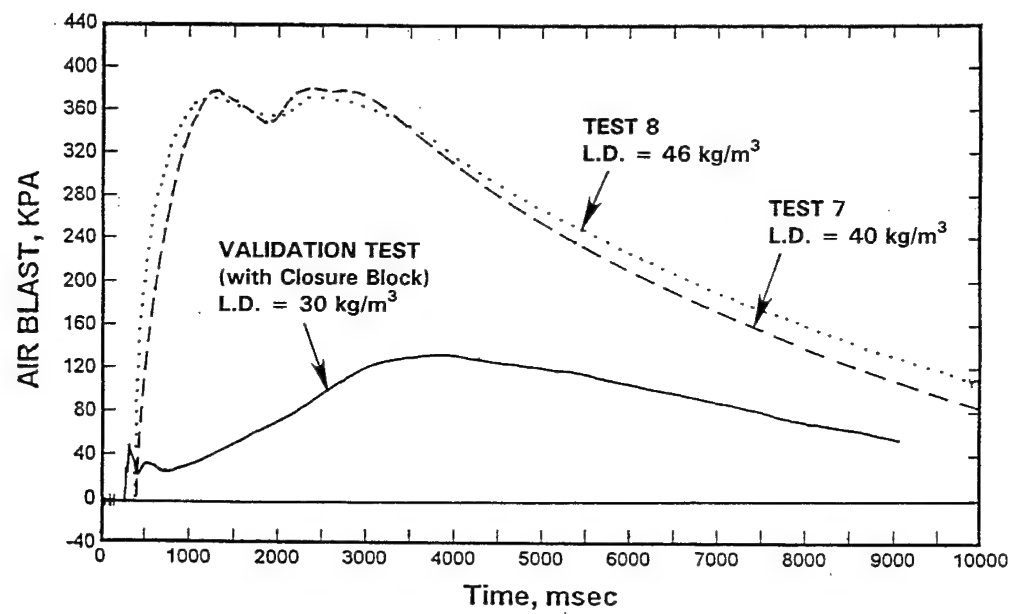
(c) Closure Break-up Begins, Gas Pressure Reaches Gage 19

(d) Failed Closure Block Passes Gage 19

Figure 3.25. The effects of the closure block movement on the downstream pressure-time history (Gage 19, located 12m from Chamber 2), from Phase 4 Validation Test.



(a) Gage 17, located approximately 17m (10 tunnel diameters) from test chambers.



(b) Gage 5, located 112m (50 tunnel diameters) from chambers.

Figure 3.26 Tunnel pressure records from 1/3-scale Validation Test compared to similar tests without closure blocks.

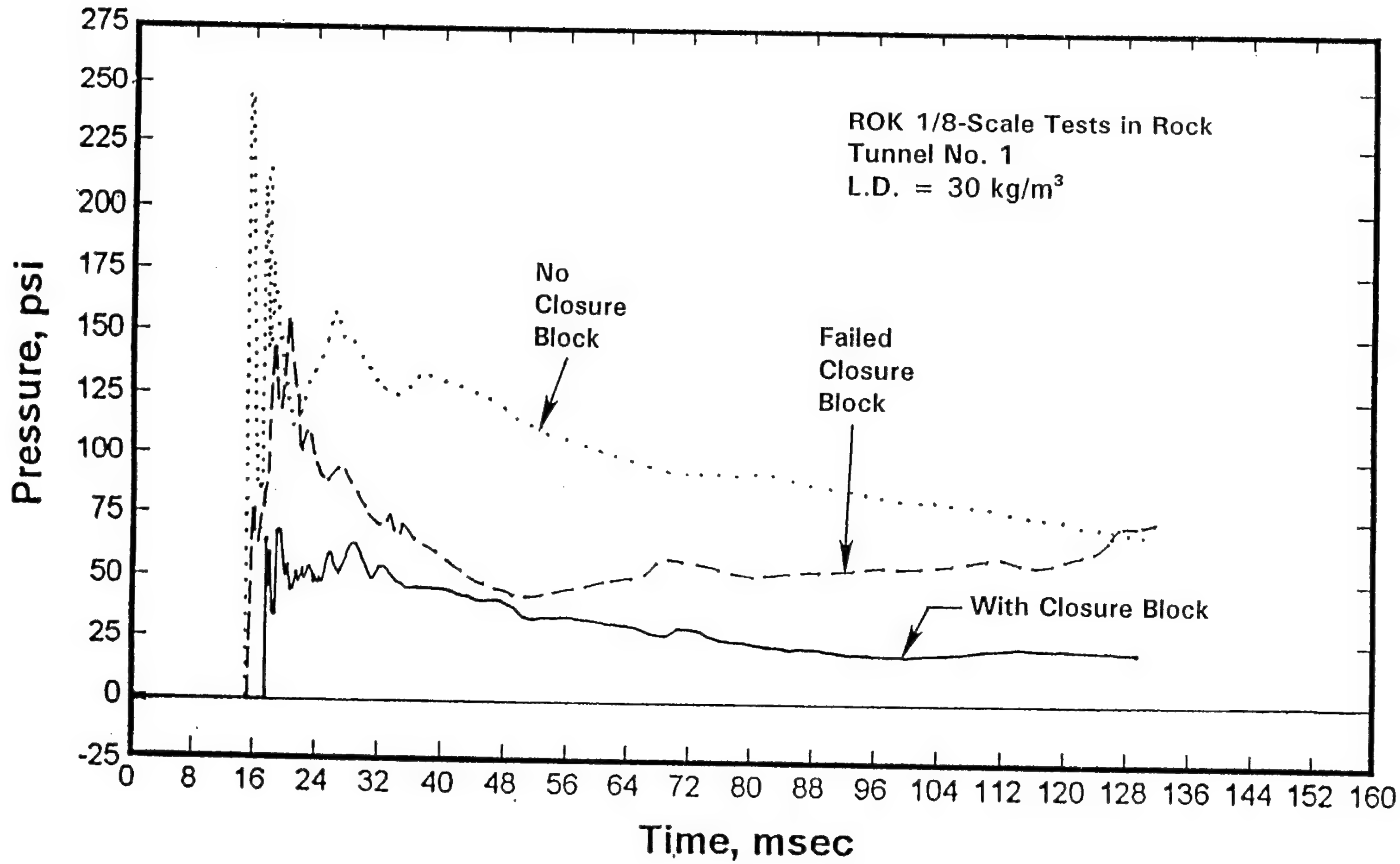


Figure 3.27 Comparison of tunnel pressure records at gage stations 17m (14 tunnel dia.) from ROK tests with and without blast-driven closure blocks.

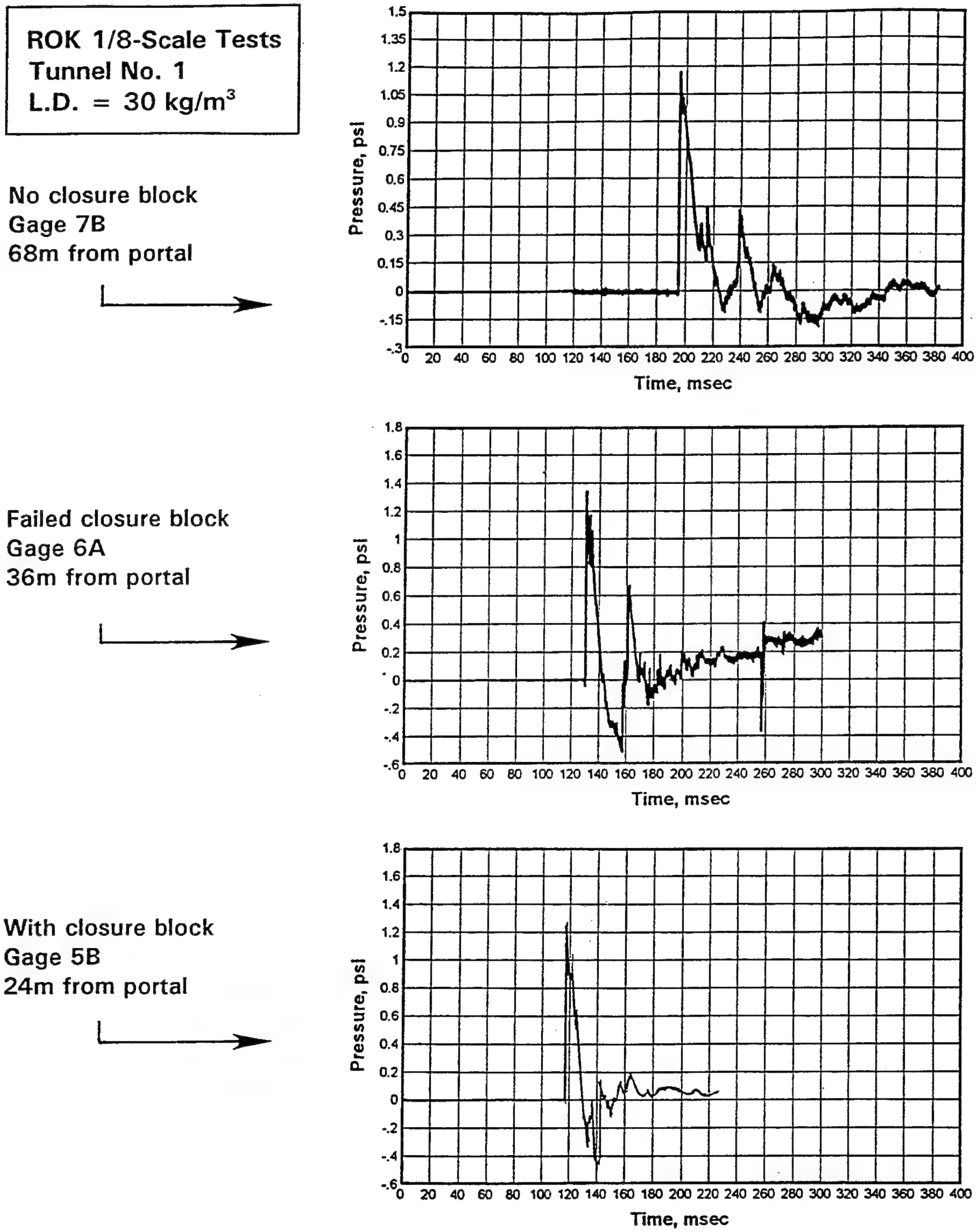


Figure 3.28 Comparison of IBD distances (to 1.2 psi, or 8.3 kPa) from ROK tests in rock chambers with and without blast-driven closure blocks.

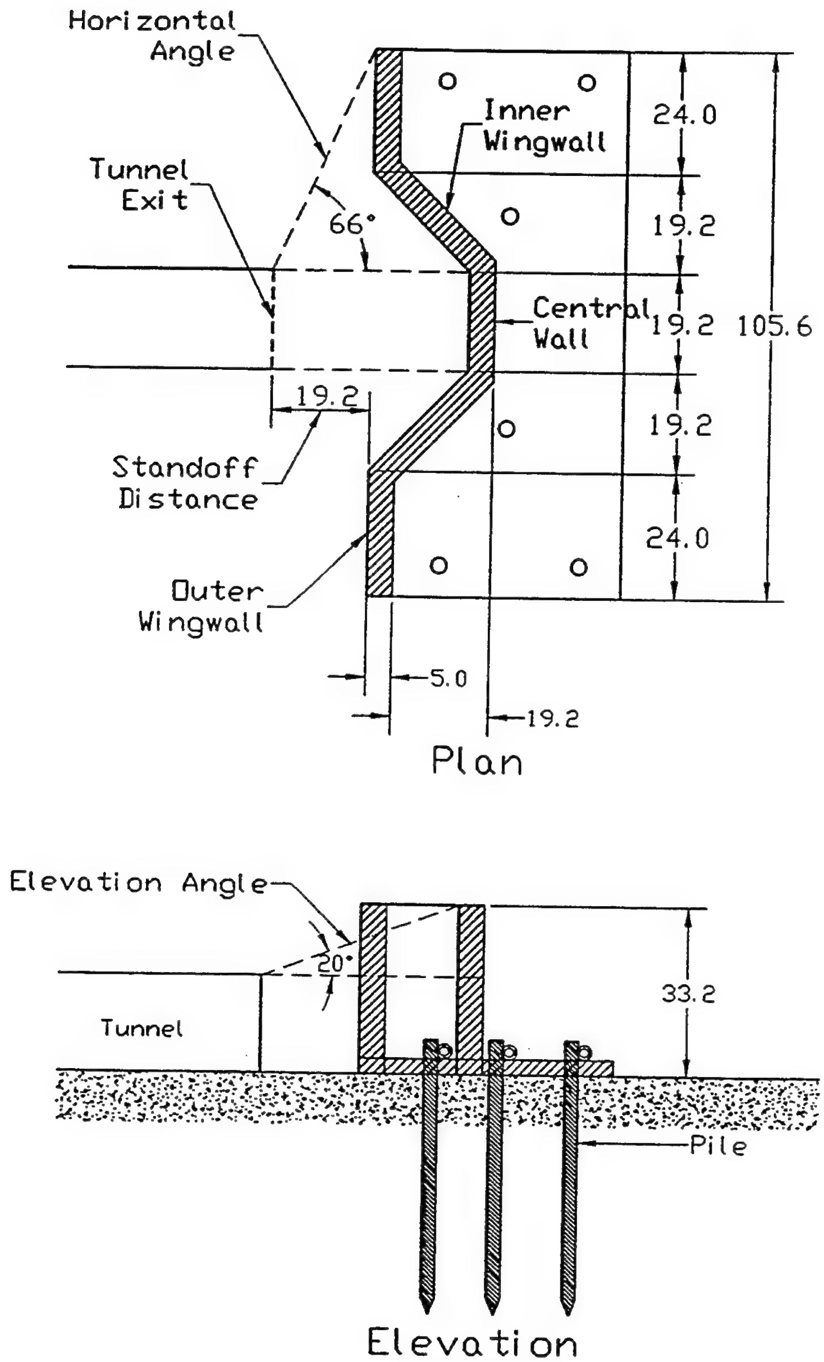


Figure 3.29 Type I barricade used in ROK Phase 4 small-scale Barricade Evaluation Study. Dimensions are in centimeters.

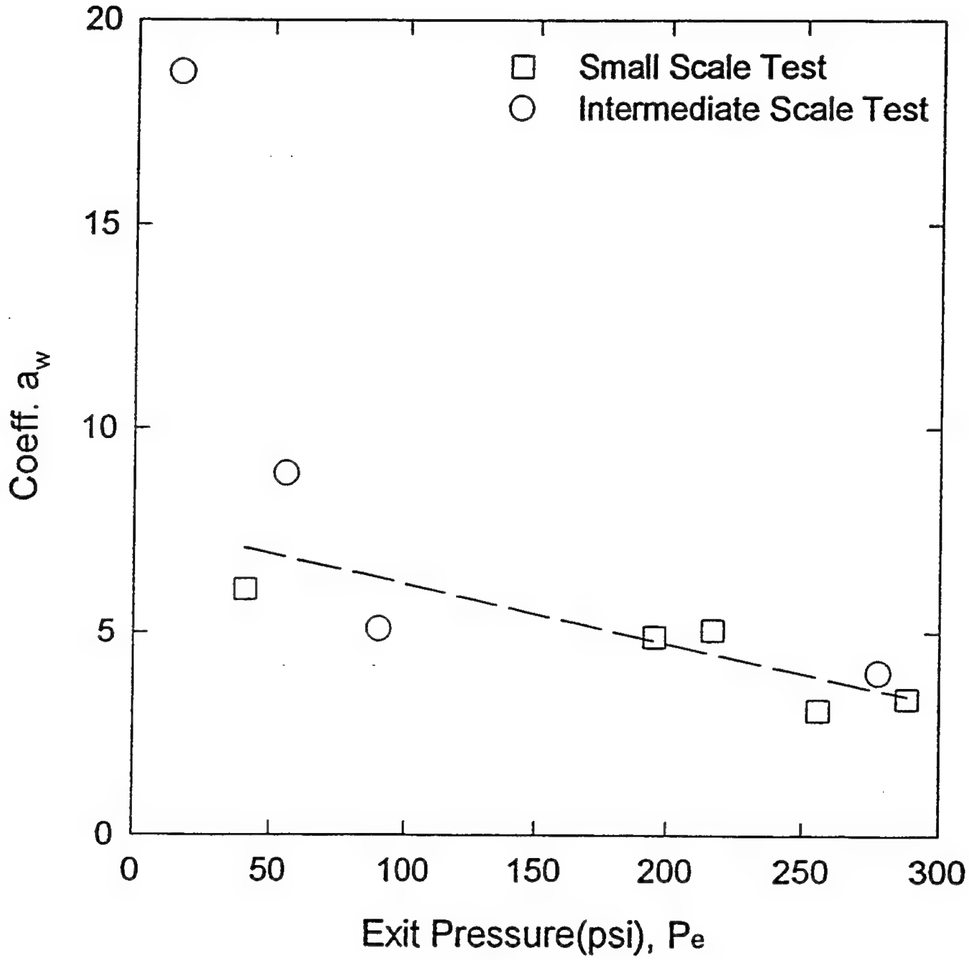


Figure 3.30 The coefficient, a_w, as a function of the tunnel exit pressure, P_e, for tests with the Type I barricade.

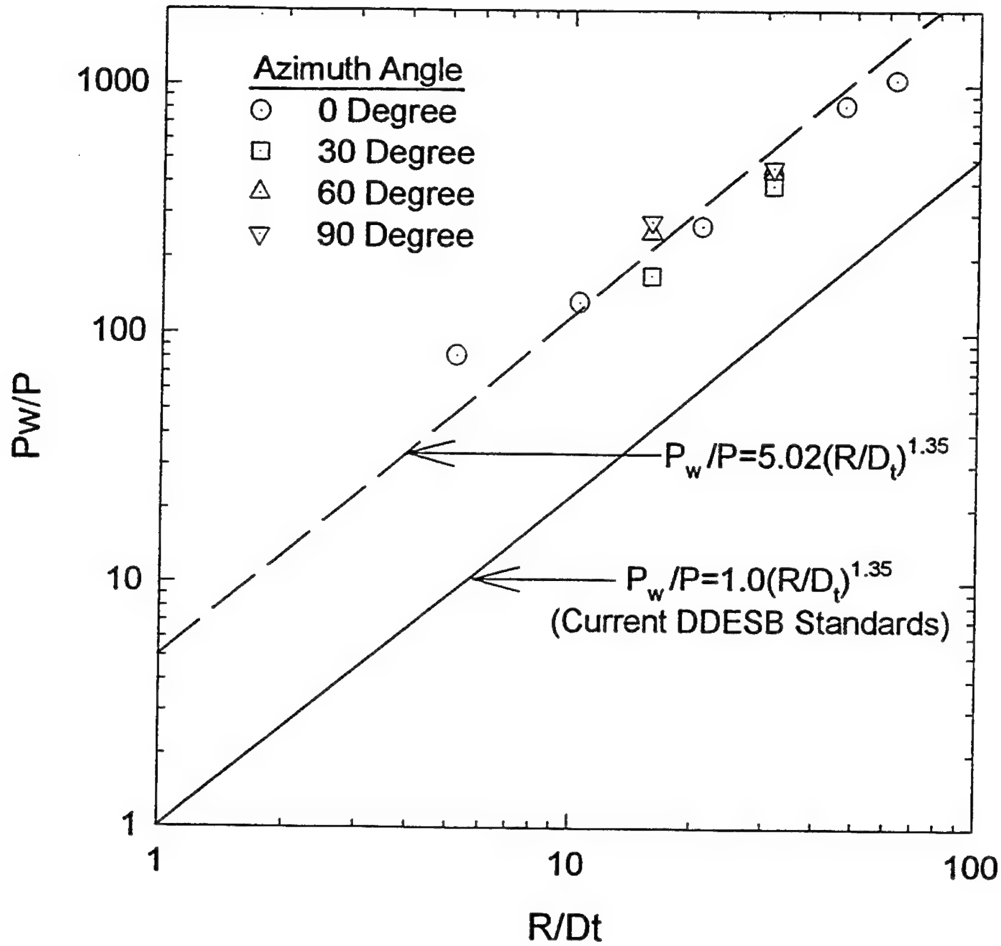


Figure 3.31 Free-field pressure as a function of azimuth angle from extended tunnel centerline and scaled distance from the portal for Type I barricade (explosive weight: 0.4 kg). Dashed curve for tests data (at 0-degree angle only) is compared with solid curve from current safety standards.

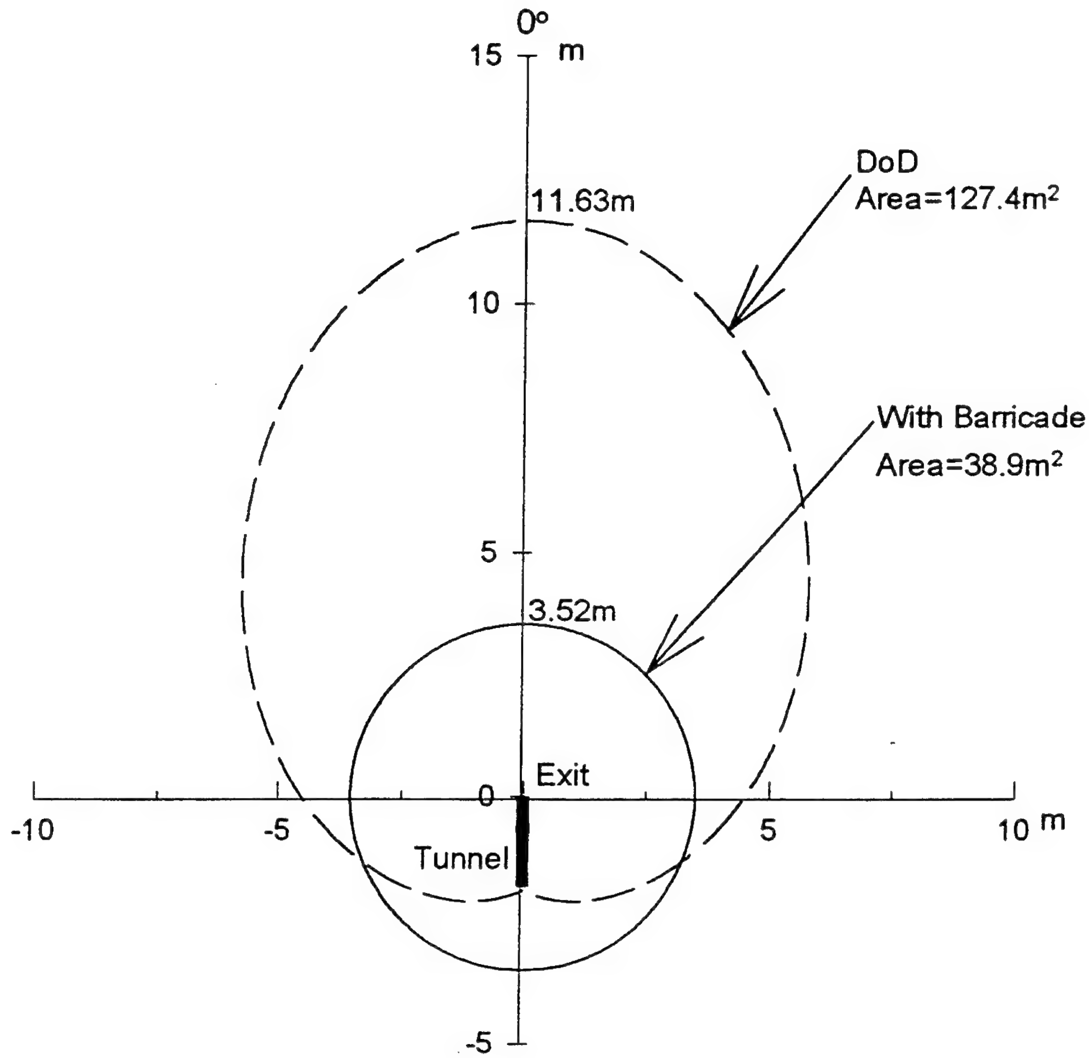


Figure 3.32 Measured hazard area for 1/30-scale test with Type 1 barricade, compared to current DoD prediction, for chamber loading density of 3.5 kg/m^3.

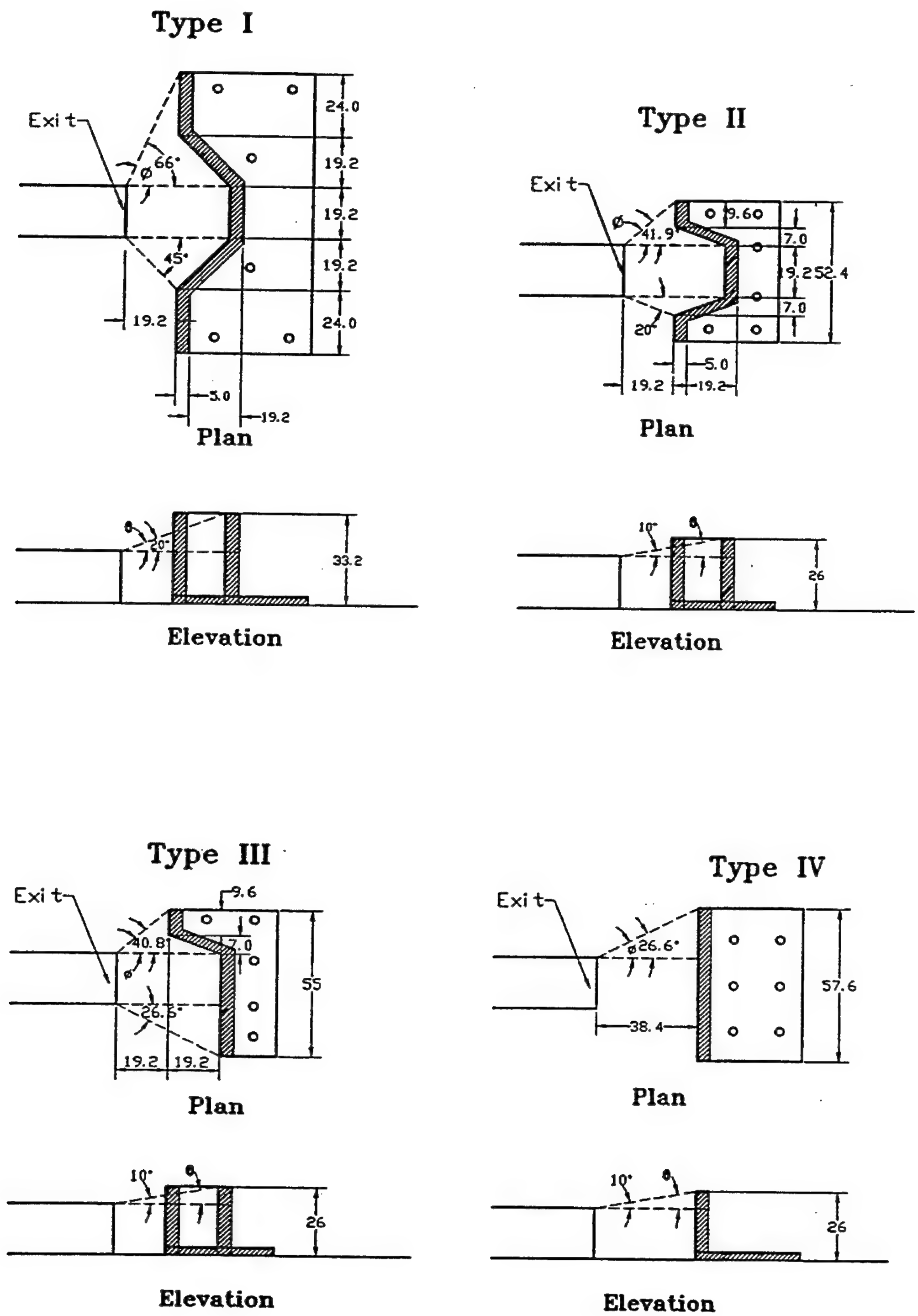


Figure 3.33 Four types of external barricades tested in Phase 4 small-scale tests. Dimensions are in centimeters.

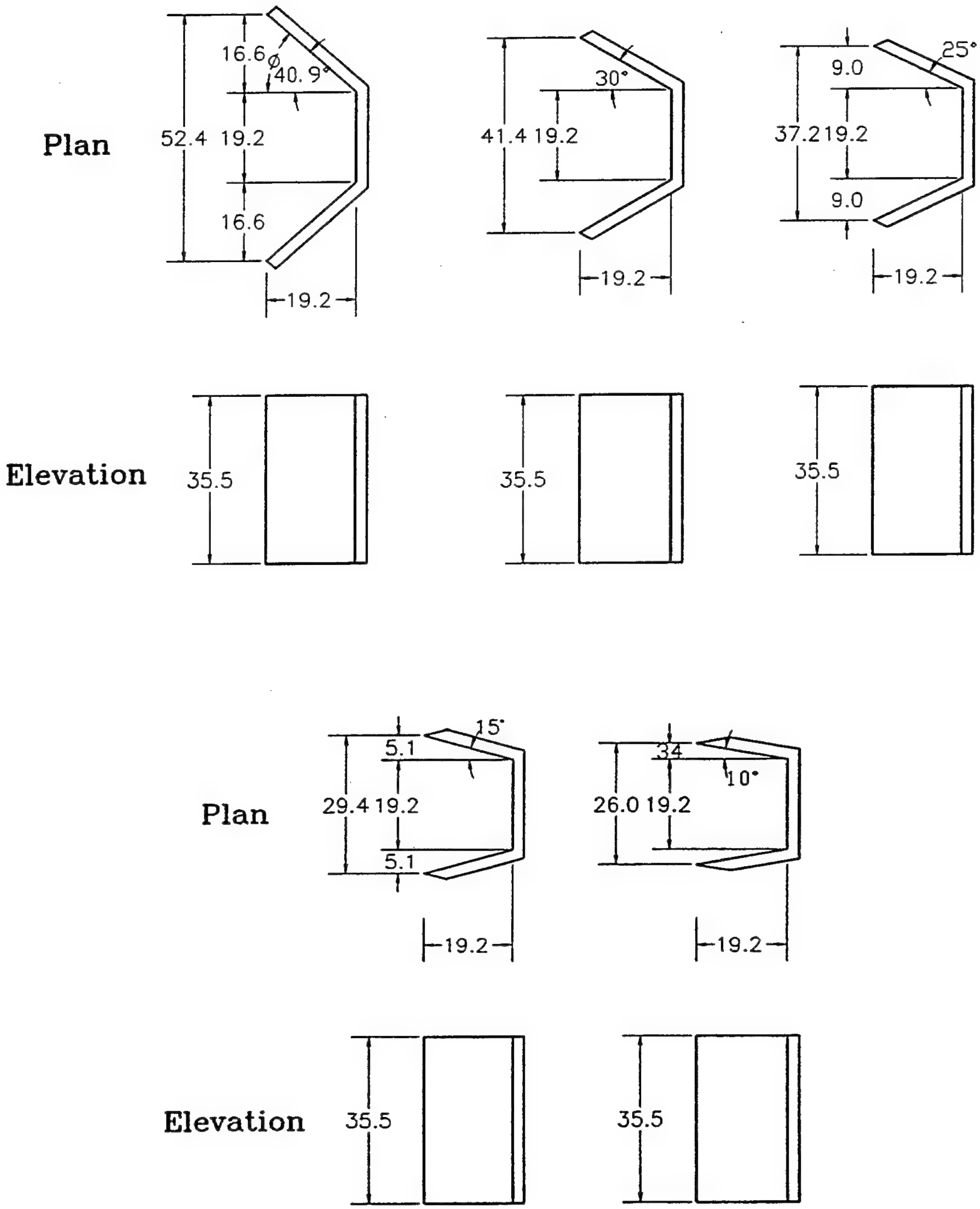


Figure 3.34 Type V external barricade, used in Phase 4 small-scale tests to investigate effect of barricade width.

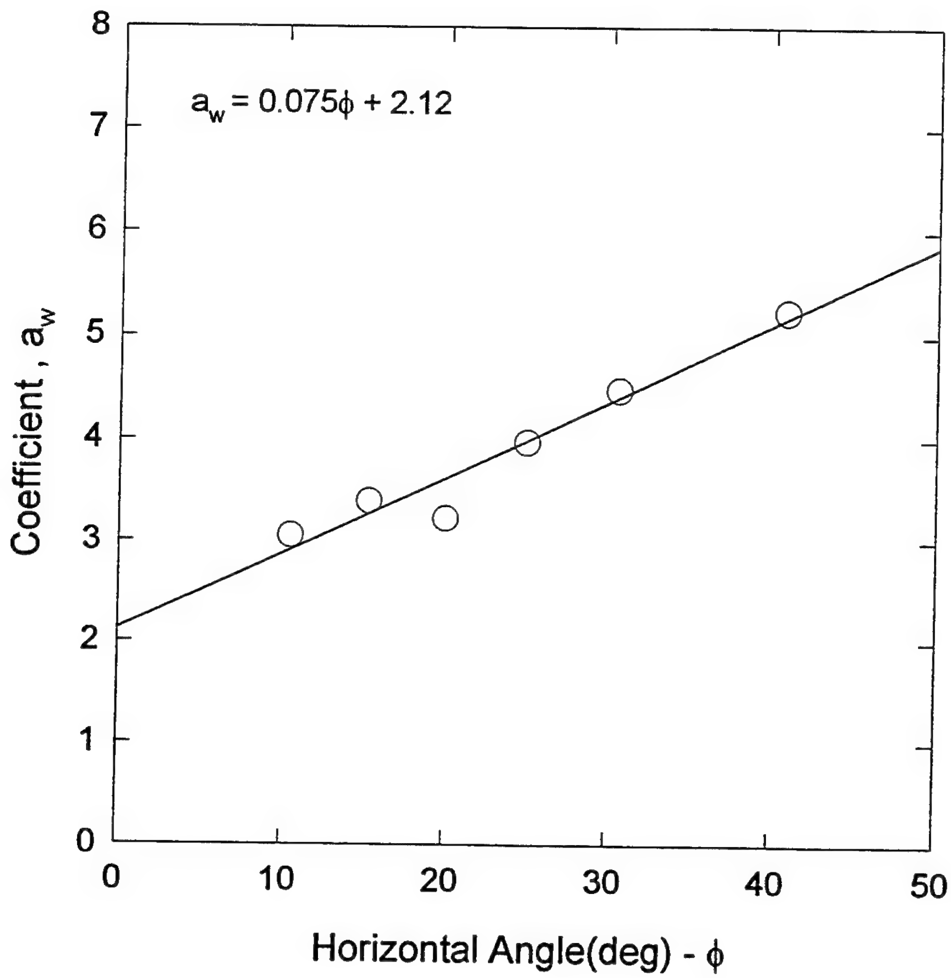


Figure 3.35 The coefficient, a_w, as a function of the horizontal angle, ϕ, from tests with Type V barricade at standoff distance of 1.0 tunnel diameters.

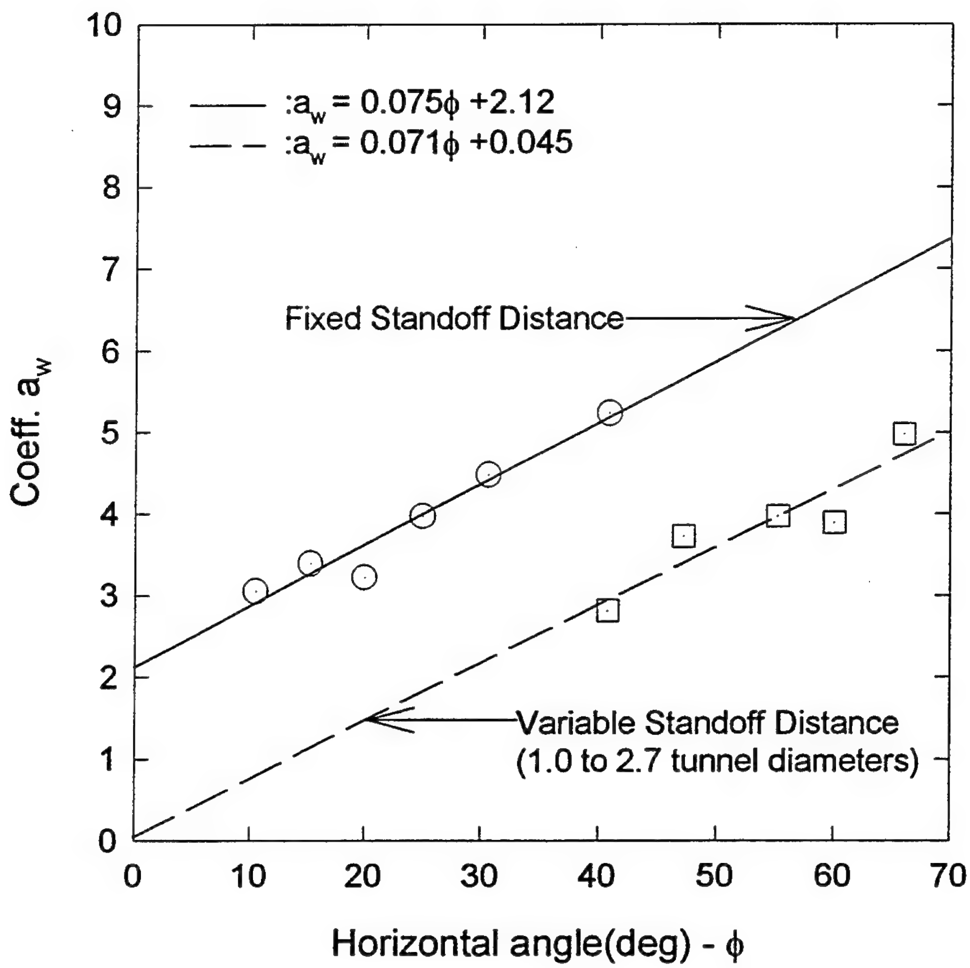


Figure 3.36 The effect of barricade stand-off distance on the coefficient, a_w, vs. the horizontal angle, ϕ.

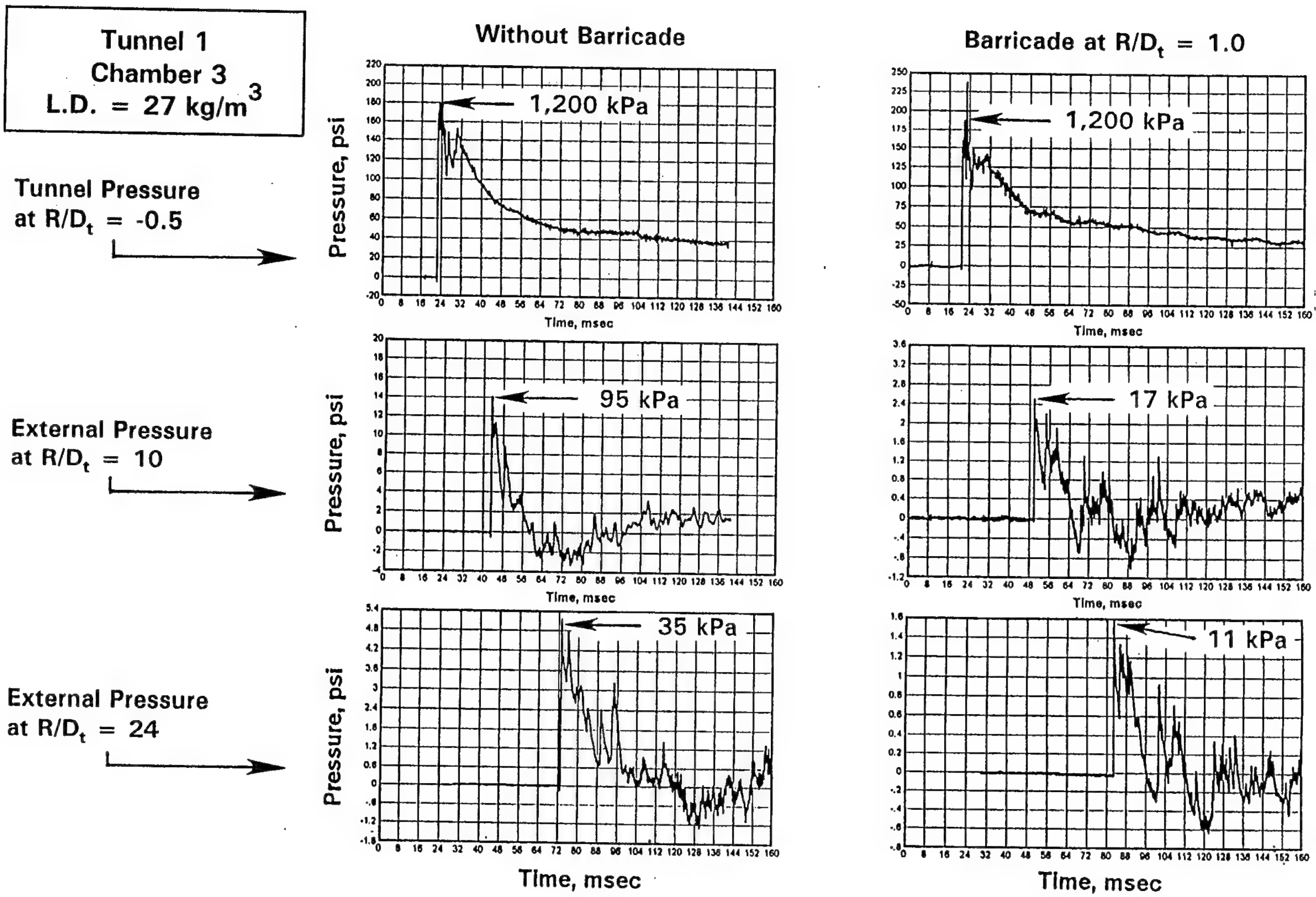


Figure 3.37 Comparisons of pressure histories recorded on ROK Phase 3, 1/8-scale tests of an underground magazine with and without a portal barricade. R is distance from the portal and D_t is the tunnel diameter.

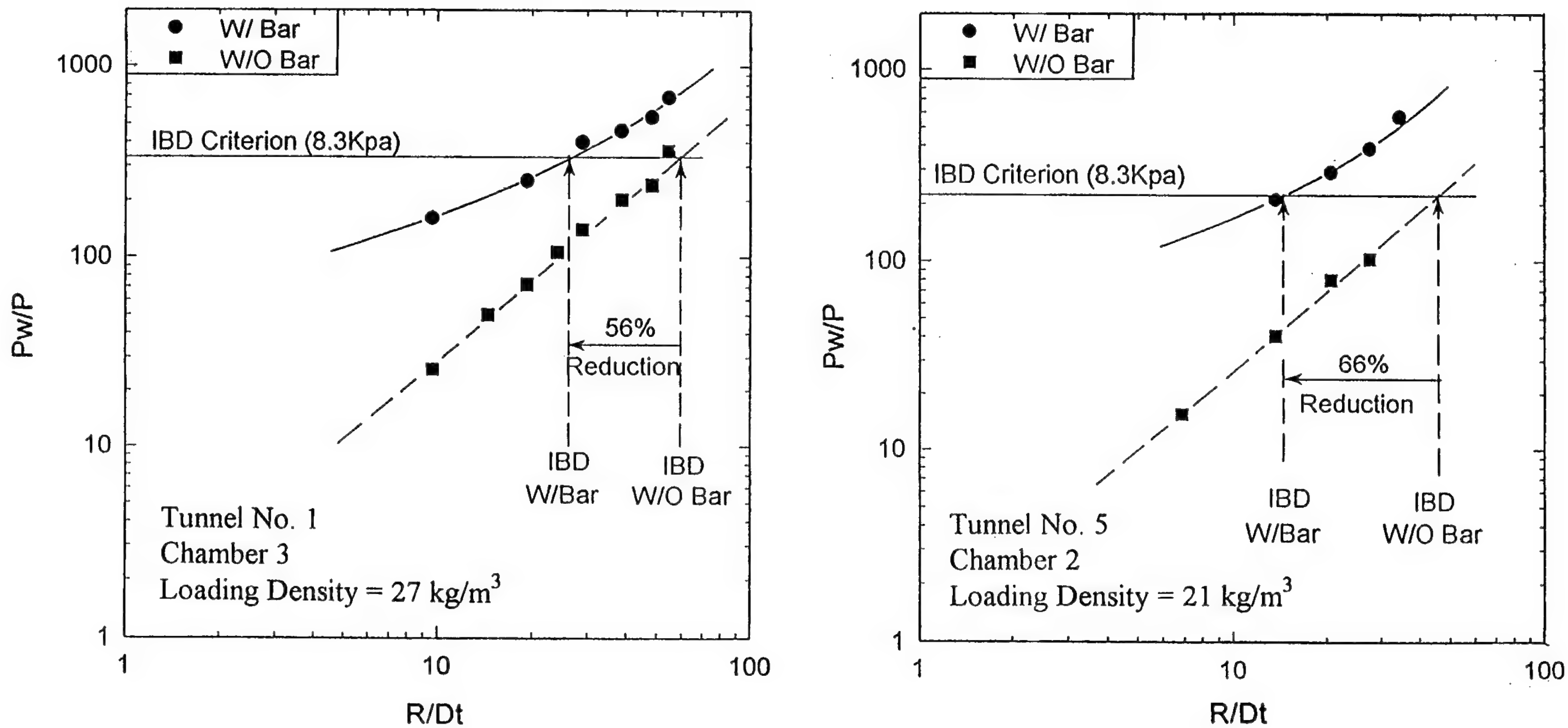


Figure 3.38 . Comparisons of free-field peak pressures and IBD's from ROK Phase 3, 1/8-scale tests of an underground magazine with (w/Bar) and without (w/oBar) a portal barricade. P_w is the tunnel exit (portal) pressure, P, is the measured free-field pressure at a range r from the portal, and D_t is the tunnel diameter.

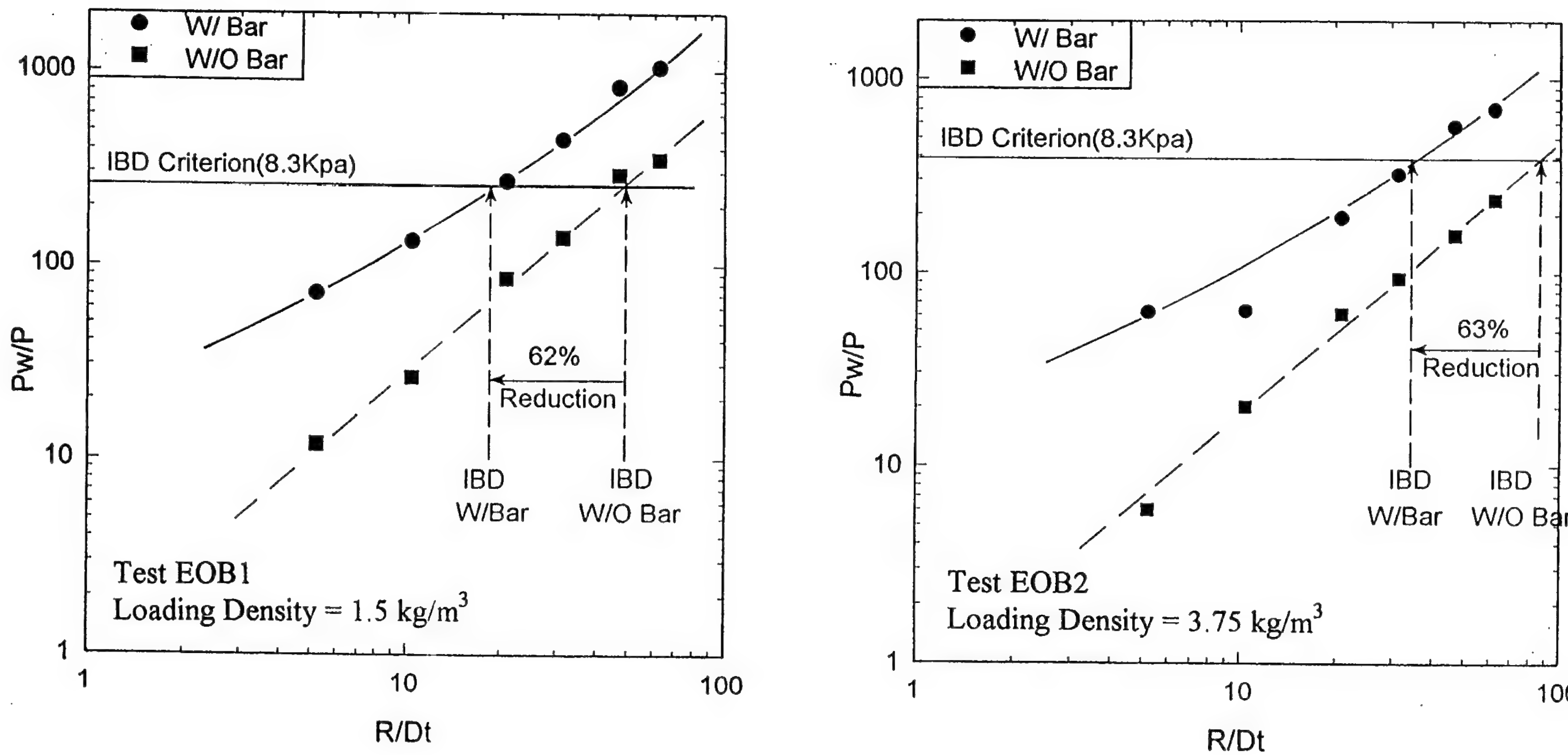


Figure 3.39 Comparisons of free-field peak pressures and IBD's from ROK 1/30-scale tests of an underground magazine with (w/Bar) and without (w/o Bar) a portal barricade. P_w is the tunnel exit (portal) pressure, P is the free-field pressure at a range R from the portal, and D_t is tunnel diameter.

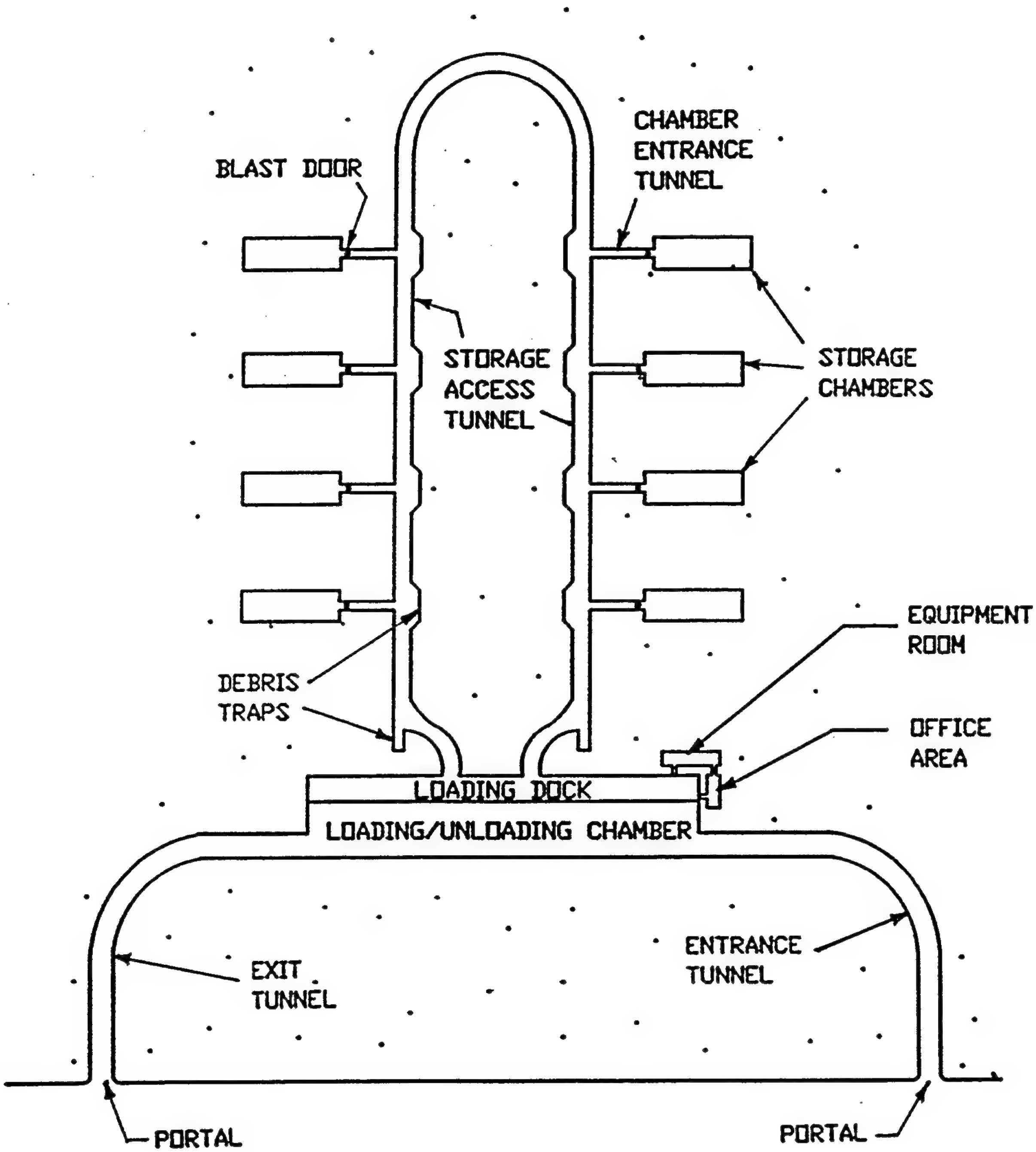


Figure 3.40 Design concept for prototype underground facility, used to identify and evaluate design, construction, operational, and maintenance problems associated with underground ammunition storage,

Table 3.1 Summary of Test Descriptions and Measured Airblast Parameters for ROK Phase 3 Intermediate-Scale Test Program

Test Magazine		Characteristics of Magazine	Explosive Weight (kg)	Chamber Loading Density (kg/m^3)	Total Loading Density (kg/m^3)	Pressure Coeff. a_w	*RHA*	Remarks
1st Tunnel	1st Chamber	Closure Block 1	243	26.4	2.46	5.10	0.09	w/o barricade
	2nd Chamber	Closure Block 2	244	29.1	2.75	2.57	0.25	w/o barricade
	3rd Chamber	Simple	244	26.7	2.97	1.39	0.61	w/o barricade
	3rd Chamber	External Barricade	244	26.7	2.67	4.00	0.24	w/ barricade
2nd Tunnel	1st Chamber	Closure Block 3	243	23.4	1.73	4.30	0.12	w/o trench barricade
	2nd Chamber	Closure Block 2	247	19.8	1.92	4.60	0.10	w/o trench barricade
	3rd Chamber	Trench Barricade	125	9.5	1.06	10.37	0.06	w/ trench barricade
3rd Chamber		Expansion Chamber, Multiple Bend	244	9.1	0.98	2.08	0.34	w/o constriction
			250	9.3	1.04	11.90	0.03	w/ constriction
4th Tunnel		Straight w/ constriction	223	25.6	3.08	1.06	0.92	
		AD8 Type	75	10.6	Left: 0.30 Right: 0.39	L: 1.43 R: 1.33	L: 0.59 R: 0.66	
5th Tunnel	1st Chamber	Closure Block 2	175	12.4	Left: 0.75 Right: 0.39	L: 2.18 R: 18.73	L: 0.32 R: 0.02	left: w/o barricade right: w/ barricade
	2nd Chamber	Simple	375	21.4	Left: 1.09 Right: 1.13	L: 1.20 R: 5.09	L: 0.76 R: 0.09	left: w/o barricade right :w/ barricade
	3rd Chamber	Closure Block 2	375	26.2	Left: 0.90 Right: 1.41	L: 8.90 R: 7.15	L: 0.05 R: 0.07	left: w/o barricade right: w/ barricade

Table 3.2 Summary of Debris Distribution Results from ROK Phase 3 Intermediate-Scale Test Program

Type of Magazine		Characteristics of Chamber	Tunnel		Free-Field		Debris Position & No. of Debris
			Debris Trap	Passageway	Barricade	Free-Field	
1st Tunnel	1st Chamber	Closure Block 1	31	58	--	4	Chamber: 700ea
	2nd Chamber	Closure Block 2	368	75	--	48	"
	3rd Chamber	External Barricade	475	39	122	12	"
2nd Tunnel	1st Chamber	Closure Block 3	113	287	--	3	"
	2nd Chamber	Closure Block 2	390	24	--	1	"
5th Tunnel	1st Chamber	Closure Block 2	210	13	--	--	Chamber: 700ea
	3rd Chamber	Closure Block 2	73	78	2	2	"
3rd Tunnel		Expansion Chamber	297	208	2	2	Chamber: 550ea Expansion Chamber: 450ea

Table 3.3 Test Parameters for U.S. Phase 3 Intermediate-Scale Tests, Linchburg Mine, Magdalena, NM

TEST No.	CHAMBER No.	EXPLOSIVE WEIGHT (COMP B) (kg)	CHAMBER VOLUME (m^3)	LOADING DENSITY (TNT Equiv.) (kg/m^3)[a]	EXPLOSIVE CHARGE (height x width x length)[b]
1	Main Drift	14.7	----	----	one cube[c] of cast Comp B
2	4	70.9	68.8	1.1	5 cubes of cast Comp B (0.2 x 0.2 x 1.0m)
3	4	343.6	68.8	5.5	24 cubes of cast Comp B (0.4 x 0.4 x 1.2m)
4	4	342.7	68.8	5.4	Flake Comp B[d] (0.5 x 0.6 x 1.5m)
5	4	942.7	71.2	14.6	66 cubes of cast Comp B (0.4 x 0.6 x 2.2m)
6	4	2569.5	75.8	37.3	180 cubes of cast Comp B (0.6 x 0.6 x 4.0m)
7	4	2888.5	80.5	39.5	279 M-15 Mines[e] (1.0 x 1.0 x 3.7m)
8	2	2797.1	66.1	46.5	270 M-15 Mines (1.0 x 1.0 x 3.6m)
9	3	2888.5	70.8	44.9	279 M-15 Mines (1.0 x 1.0 x 3.7m)
10	1	342.7	69.1	5.5	24 cubes of cast Comp B (0.4 x 0.4 x 1.2m)

(Continued)

Table 3.3 (Concluded)

TEST No.	CHAMBER No.	EXPLOSIVE WEIGHT (COMP B) (kg)	CHAMBER VOLUME (m^3)	LOADING DENSITY (TNT Equiv.) (kg/m^3)[a]	EXPLOSIVE CHARGE (height x width x length)[b]
11	1	332.1	69.1	5.3	32 M-15 Mines (Comp B) (0.3 x 0.6 x 1.9m)
12	1	343.1	69.1	5.5	155 mm M107 projectiles[f] (Comp B); TNT supplemental charge, C-4 boosters
13	Expansion Chamber	116 (Nitromethane explosive)	____[g]	Fully Coupled	(0.3m dia. x 1.4m long vertical cylinder)

[a] Assuming TNT equivalence factor of 1.1 for Composition B

[b] All charges (except Test 13) had their long axis aligned with the long axis of chambers. All charges, (except those of Tests 1, 12 and 13) were placed on wood platforms, with centerline of charges at mid-height of chambers.

[c] 203 mm cube suspended in center of Linchburg Mine drift.

[d] Flake Comp B placed in plywood box.

[e] M-15 mines were stacked on their sides, with top of first mine against bottom of second mine, etc.

[f] Pallets of artillery projectiles (eight per pallet) were placed on the floor of the chamber. Charge weight includes 8.2 kg of TNT and C-4 booster explosives.

[g] Charge was placed in a stemmed, 40cm-diameter hole, with center of charge 7.4m below the floor of the expansion chamber.

Table 3.4 Effect of Barricade Horizontal Angle on External Airblast (see Figure 3.34).

Horizontal Angle (degrees)	Pressure Coefficient, a_w
10.5	3.05
15.3	3.39
20.0	3.22
25.0	3.97
30.6	4.44
40.9	5.24

Table 3.5 Effect of Barricade Elevation Angle on External Airblast

Elevation Angle (degrees)	Pressure Coefficient, a_w
8.6	3.20
10.0	2.88
12.1	2.73
14.0	2.97
16.0	2.86
18.0	3.06
20.0	3.02
23.0	3.39

PART 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The Joint US/ROK R&D Study for New Underground Ammunition Storage Technologies was a comprehensive and intensive investigation of the hazards produced by accidental explosions of ammunition stored in underground magazines, methods for predicting the hazards, and techniques by which the hazard areas outside the storage facilities could be reduced. Although the study relied heavily on small-scale and intermediate-scale tests, care was taken to ensure that the results could be accurately "scaled" up for application to full-scale facilities. When the results could not be scaled with confidence, a safety-conservative interpretation of the data was made.

The original objective of the study was to "develop, test, and validate new underground explosive storage techniques which, when utilized, will reduce explosives storage hazards with no reduction in security, operational readiness, or logistical support." This objective has clearly been achieved. In fact, the study has shown that underground magazines can be constructed and operated in a manner that will reduce, *by 90 percent or more*, the amount of real estate required to meet current military safety standards for long-term ammunition storage facilities. No evidence of any adverse effect on logistical support was found. With regard to security and readiness, underground magazines will, in fact, provide major benefits. Security can be greatly increased, with a reduction in manpower. Readiness is significantly enhanced by the near-total protection of ammunition assets against enemy weapons, and the ability to sort and load ammunition in a protected (underground) environment.

A special study was performed---independently from the main R&D program---to assess the potential applicability of the underground ammunition storage concepts to U.S. Army installations in the continental U.S. Although the full extent of hazard area reduction achieved by the UAST program had not been defined at the time, the study still found that underground

storage was, in most cases, a much better alternative to the present above-ground storage for future storage requirements. This was largely due to the very strong benefits for environmental and land use concerns.

4.2 RECOMMENDATIONS

This joint U.S./Korea research program was a cooperative effort in the true sense of the term. In spite of the great distances separating the U.S. and Korean research teams physically, culturally, and language-wise, a strong partnership and a close working relationship were established that produced an effective and well-balanced R&D effort. It is strongly recommended that similar cooperative programs be organized to address future R&D problems of common interest.

The R&D findings produced by the program were routinely reviewed for accuracy and validity by the U.S. and ROK Technical Advisory Groups, and the recommended revisions of the present safety standards have been submitted to, and approved by, the U.S. DoD Explosives Safety Board and the ROK Explosives Safety Management Board. It is therefore recommended that the underground ammunition storage concepts advocated by the program be pursued to the fullest extent practical by Korean and U.S. military users.

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APPENDIX A

PROPOSED REVISIONS TO U.S. DOD AMMUNITION AND EXPLOSIVES SAFETY STANDARDS (DOD 6055.9-STD)

(Note: Page numbers refer to pages in October 1992 edition
of DoD 6055.9-STD)

to as exterior or leakage pressures, once released from their confinement, expand radially and act on structures or persons, or both, on the other side of the barrier.

C. EXPECTED EFFECTS - HAZARD DIVISION 1.1

1. Conventional Structures. Conventional structures, which include most aboveground magazines and inhabited buildings, are designed to withstand roof snow loads of 30 pounds per square foot (1.44 kPa) and wind loads of 100 miles per hour (161 kilometers per hour). The loads equate to 0.2 pounds per square inch (psi). Airblast overpressure at Hazard Division 1.1 barricaded intraline distance is 12 psi (82.7 kPa); at unbarricaded intraline distance is 3.5 psi (24 kPa); and at inhabited building distance is 0.9 to 1.2 psi (6.2 to 8.3 kPa). Comparing these loads with the design capacity, it is evident that conventional buildings will be damaged even at inhabited building distance. Conventional structures, which include aboveground storage facilities, contribute little to propagation protection from either blast or fragments. Propagation protection is provided by distance and/or barricading. The amount of damage to be expected at various pressure levels is described below.

2. Earth-Covered Magazines. The earth-covered magazines identified in section B., Chapter 5, separated one from another by the minimum distances required by Table 9-5, provide virtually complete protection against propagation of explosion by blast, fragments, and fire; however, there may be some cracking of concrete barrels and rear walls, possible severe cracking and some spalling of front walls, and some damage to doors and ventilators.

3. Underground Storage Facilities. Underground facilities sited and constructed as specified in Chapter 9 provide a high degree of protection against propagation of explosion between chambers by blast, fragments or spall, and between underground and aboveground structures. Delayed propagation between chambers by fire is possible, but this possibility may be minimized by installation of a fire suppression system.

4. Barricaded Open-Storage Modules. Barricaded open-storage modules (sub-section B.3., Chapter 5) provide a high degree of protection against propagation of explosion by blast and fragments. However, if flammable materials are present in nearby cells, subsequent propagation of explosion by fire is possible. Items at K=1.1 separations from a donor explosion will be covered with earth and unavailable for use until extensive uncovering operations and possibly maintenance are completed. Items at K=2.5 separations are expected to be readily accessible.

5. Barricaded Aboveground Magazine Distance - $6W^{1/3}$ ft ($2.4Q^{1/3}$m) - 27 psi (186.1 kPa)

a. Unstrengthened buildings will be destroyed completely.

b. Personnel at this distance or closer will be killed by direct action of blast, by being struck by building debris, or by impact against hard surfaces.

F. THERMAL HAZARD

1. General. The energetic materials used by Department of Defense all produce an exothermic reaction defined either as a deflagration or a detonation. A deflagration is an exothermic reaction that propagates from the burning gases to the unreacted material by conduction, convection, and radiation. In this process, the combustion zone progresses through the material at a rate that is less than the velocity of sound in the unreacted material. In contrast, a detonation is an exothermic reaction that is characterized by the presence of a shock wave in the material that establishes and maintains the reaction. A distinctive difference is that the reaction zone propagates at a rate greater than sound velocity in the unreacted material. Every material capable of detonating has a characteristic velocity that is under fixed conditions of composition, temperature, and density.

2. Permissible Exposures. Personnel shall be provided protection that will limit thermal fluxes to 0.3 calories per square centimeter per second when hazard assessments indicate the probability of accidental explosions is above an acceptable risk level as determined on a case-by-case basis by the DoD Component concerned.

G. Ground Shock.

1. General. Ground shock from explosions in underground facilities may endanger assets in neighboring chambers and produce damage to buildings on the surface. Protection of assets can be achieved by proper chamber separation distance and design. Distance requirements to protect surface structures are dependent upon site specific geological conditions, as well as NEW and chamber loading density. Chapter 9 details quantity distance requirements for ground shock protection from explosions in underground facilities.

2. Permissible Exposures. Procedures for predicting ground shock and calculating Q-D to protect facilities are in Chapter 9.

H. CHEMICAL AGENT HAZARDS

These items are covered in Chapter 11.

equal number of propelling charges may be stored with the separate loading projectiles.

3. The Q-D requirements in Chapter 9 shall be applied to the storage locations addressed in subsection E.2. above.

F. UNDERGROUND STORAGE

Ammunition with smoke producing, incendiary, flammable liquid or toxic chemical agent fillers may be stored in single chamber underground facilities but shall not be stored in multi-chamber facilities. Other than this restriction, ammunition and explosives of all compatibility groups may be placed in underground storage in compatible combinations as permitted above.

Redesignate 3.F. thru 3.M. to 3.G. thru 3.N.

G. EXPLOSIVES HAZARD CLASSIFICATION PROCEDURES

DoD Explosives Hazard Classification Procedures (TB 700-2, NAVSEAINST 8020.8A, TO 11A-1-47 and DLAR 8220.1, reference (d)) shall be used as a basis for assignment of hazard divisions to all ammunition and explosives except those that are candidates for designation as extremely insensitive detonating substances (EIDS) and EIDS ammunition. EIDS and EIDS ammunition shall be assigned to hazard divisions as indicated in section K., below.

H. EIDS AND EIDS AMMUNITION

1. EIDS comprises Hazard Division 1.5 type explosive substances that, although mass detonating, are so insensitive that there is negligible probability of initiation or transition from burning to detonation in storage.

2. EIDS ammunition, Hazard Division 1.6, is ammunition that contains EIDS and that has demonstrated through test results (section K., below) that the mass and confinement effects of the ammunition case are negligible on the probability of initiation or transition from burning to detonation of the EIDS in transport or storage. Such ammunition when intentionally initiated will be incapable of transferring detonation to another (that is, propagating).

(2) Separation Between Modules and All Other Targets

(a) Distance between a module and other magazines shall be determined by applying the intermagazine distances specified in Tables 9-4 and 9-5.

(b) Distances between the explosives in the cells of a module and all other targets shall be determined upon the basis of the NEW of single cells. Distances shall be measured between the nearest edge of the munitions stack in the "controlling" cell and the nearest point of the target concerned (see subsection B.2. of Chapter 9).

4. Underground Magazines. No specific limitation on NEW applies to these facilities or to individual chambers within facilities. Explosives limits will be based upon equations or table values in section G. of Chapter 9.

5. Other Magazines. Existing magazines described by definitive drawings and specifically approved for the purpose by DoD Components are approved for storage of ammunition and explosives. Prior DDESB safety review and approval (section F., below) are required for new types of ammunition and explosives storage facilities and for existing facilities first being proposed for use in storing ammunition and explosives.

6. Magazine Siting Requirements

a. Magazines are sited with respect to each other (that is, intermaga- zine distance) so that communication of explosion from one to another is unlikely to occur. Actual siting requirements are influenced both by the construction features of the magazines, and the types and quantities of ammunition and explosives they contain. Magazines identified in subsection B.1., above, have proven capabilities for explosion communication prevention for all types of ammunition and explosives. Magazines identified in subsection B.2., above, are weaker structurally and thus have lesser capabilities for prevention of explosion communication. If the specified thickness and slope of earth on magazines listed in subsection B.1., above, are not maintained, the quantity of Hazard Division 1.1 stored therein shall be limited to a maximum of 250,000 lbs and Table 9-1, columns 5 and 9 Q-D shall apply.

b. For application of specified Q-D to magazines listed in subsection B.1., above, they must not be weakened structurally to the extent that they could not be expected to prevent explosion communication.

c. Determination whether construction of magazines is equivalent to the requirements of the applicable drawings will be made by the DoD Component concerned.

d. Further construction of standard earth-covered magazines must meet the minimum requirements of the current revisions of the drawings listed in subsection B.1., above.

e. Normally, earth-covered magazines will not be constructed to face door-to-door. They should face in the same direction with long axes parallel to each other. In special cases, when topographic or other important considerations would result in different orientations, they will be sited in accordance with paragraph C.1.c. of Chapter 9.

f. Specific siting requirements for underground storage facilities are contained in section G. of Chapter 9.

C. BARRICADES AND EARTH COVER FOR MAGAZINES

1. a. General. Properly constructed barricades or undisturbed natural earth are effective means for protecting ammunition or explosives, structures, or operations against high-velocity, low-angle fragments although the barricades may be destroyed in the process. Since such fragments move along ballistic trajectories rather than straight lines, reasonable margins in barricade height and length must be provided beyond the minimum dimensions that block lines of sight. Barricades also provide limited protection against blast in the immediate vicinity. They do not provide any protection against high angle fragments and are ineffective in reducing the blast pressure in the far field (inhabited building or public traffic route distance).

b. Underground storage facilities present special conditions that must be accounted for in portal barricade design. Specific criteria for location and construction of portal barricades for these facilities are found in paragraph C.5. of Chapter 5, below.

2. Barricade requirements for Other Than Underground Facilities. Protection is considered effective when barricades meet the following minimum requirements:

a. The slope of a barricade may not be steeper than 1 1/2 horizontal to 1 vertical in order to meet explosives safety requirements. Facilities constructed in the future should have a slope of 2 horizontal to 1 vertical to reduce erosion and facilitate maintenance operations.

b. Earth barricades shall be made of material as indicated in subsection C.4., below.

c. Determine the height and length of barricades as follows:

(1) Height. Establish a reference point at the top of the far edge of one of the two stacks under consideration between which the barricade is to be constructed. This reference point, if the top of the stacks are not at the same elevation, shall be on the stack whose top is at the lower elevation. Draw a line from the reference point to the highest point of the other stack. Draw a second line from the reference point forming an angle of 2 degrees above the line. To preclude building excessively high barricades, the barricade should be located as close as possible to the stack on which the reference point was established. When the stacks are of equal height, the reference point may be established on either stack. See Figure 5-2.

(2) Length. The length of the barricade shall be determined as shown in Figure 5-3.

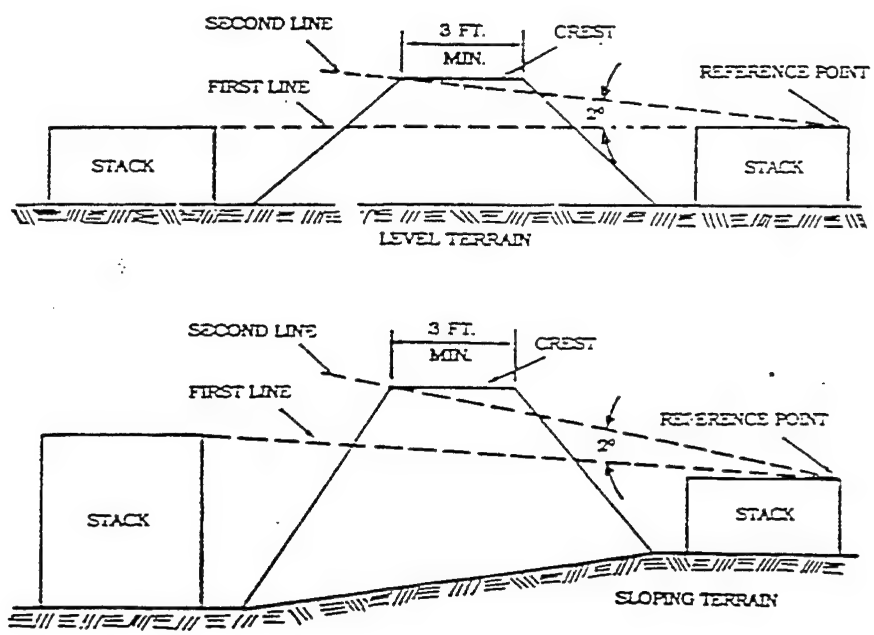


Figure 5-2. Determination of Barricade Height

d. Earth barricades that meet the above requirements may be modified by substituting a retaining wall, preferably of concrete, for the slope on one side. The remaining side shall be of such slope and thickness as necessary to ensure that the width of earth required for the top is held firmly in place.

e. Other intervening barriers meeting the above requirements or proven effective by test also may be used, for example, earth-filled steel bin barricades for explosives-loaded aircraft. Barricades meeting the above requirements may be found in Army drawing 149-30-01.

3. Location of Barricades

a. The distance between the foot of the barricade and the stack of ammunition or explosives or buildings containing explosives is necessarily a compromise. The smaller the distance, the less the height and length of the barricade required to secure proper geometry for intercepting projections. On the other hand, it may be essential to make the distance great enough to provide access for maintenance and vehicles.

b. If it is impracticable to locate the barricades as stated in paragraph C.3.a., above, barricades may be located adjacent to the facility to be protected.

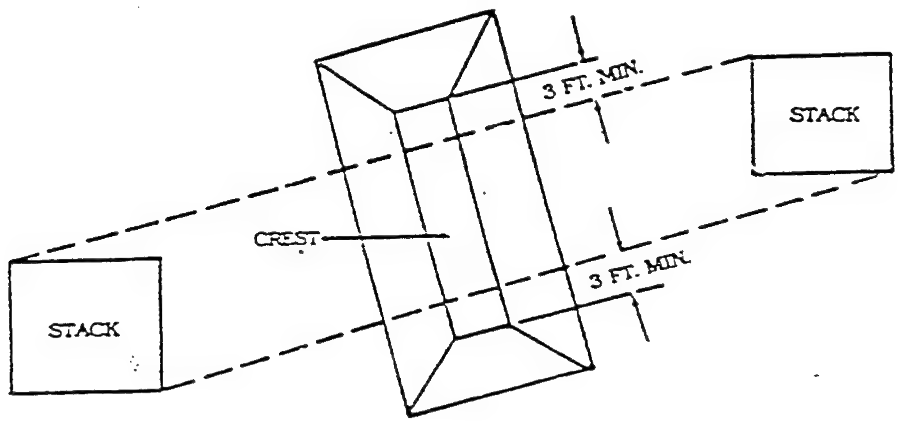


Figure 5-3. Determination of Barricade Length

4. Earth Cover for Magazines and Barricades

a. Material for earth cover over magazines and for barricades shall be reasonably cohesive (solid or wet clay or similar types of soil may not be used as they are too cohesive), free from deleterious organic matter, trash, debris, and stones heavier than 10 pounds or larger than 6 inches in diameter. The larger stones shall be limited to the lower center of fills and will not be used for earth cover over magazines. Compaction and surface preparation shall be provided, as necessary, to maintain structural integrity and avoid erosion. When it is impossible to use a cohesive material, for example, in sandy soil, the barricade or the earth cover over magazines shall be finished with a suitable material to ensure structural integrity.

b. The earth fill or earth cover between igloo magazines may be either solid or sloped in accordance with the requirements of other construction features, but a minimum of 2 feet or earth cover shall be maintained over the top of each magazine and a minimum slope of 1 1/2 horizontal to 1 vertical starting directly above the spring line of each arch shall be maintained to meet explosives safety requirements. Facilities constructed in the future shall have a slope of 2 horizontal to 1 vertical to reduce erosion and ease maintenance operations.

5. Portal Barricades for Underground Magazines.

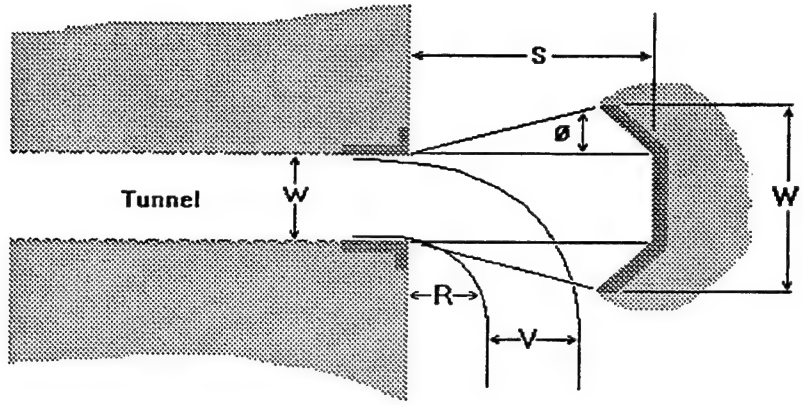
a. Portal barricades for underground magazines are located immediately in front of an outside entrance or exit (i.e., the portal)to a tunnel leading to an explosives storage point. The portal barricade should be centered on the extended axis of the tunnel that passes through the portal. Specific design criteria for a portal barricade are given in the Corps of Engineers definitive drawing number DEF 421-80-04. The remaining narrative of this paragraph is given for conceptual guidance. For maximum effectiveness, the front face (i.e., the face toward the portal) of the barricade mus be vertical and concave in plan, consisting of a central face oriented perpendicular to the tunnel axis, and wingwalls on either side that are angled at 45-degrees toward the portal, as shown in Figure 5-4. The width of the central face typically equals the width of the tunnel at the portal. The wingwalls must be of sufficient width so that the entire barricade length intercepts an angle of ten degrees (minimum) to the right and left of the extended tunnel width. Likewise, the height of the barricade along its entire width must be sufficient to intercept an angle of ten degrees above the extended height of the tunnel.

b. Portal barricades for underground magazines must be located a distance of not less than one and not more than three tunnel widths from the portal. The actual distance should be no greater than that required to allow passage of any vehicles or materials handling equipment that may need to enter the tunnel. As shown in Figure 5-4, this distance is based on the turning radius and operating width required for the vehicles or equipment.

c. To withstand the impact of debris ejected from the tunnel, the front face of the portal barricade (including wingwalls) must be constructed as a wall of reinforced concrete, with a minimum thickness equal to 10 percent of the barricade height, but in no case less than 12 inches. The concrete wall must have a spread footing of sufficient width to prevent significant settlement, and the central wall, wingwalls, and footing must be structurally tied together to provide stability. The backfill behind the concrete wall may be composed of any fill material, including rock rubble from the tunnel excavation, with a maximum particle size of six inches within the area extending out to three feet from the rear face of the wall.

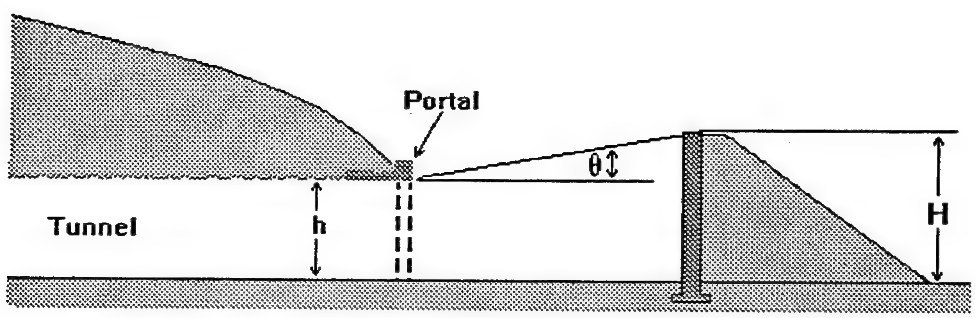
D. POLICY ON PROTECTIVE CONSTRUCTION

Advances in protective construction permit achievement of any calculated level of protection from explosion communication between adjacent bays or buildings, for personnel against death or serious injury from incidents in adjacent bays or buildings, and for vital and expensive equipment installations.
Therefore, the major objectives in facility planning shall be:



a. Plan View

S = Barricade standoff distance
w, W = Widths of tunnel and barricade
V, R = Width and turning radius of vehicles or materials handling equipment
ø = Side angle (10 degrees minimum)



b. Side Elevation

C = Crest width (See DEF 421-80-04)
h, H = Heights of tunnel and barricade
P = Elevation angle (10 degrees minimum)

Figure 5-4. Portal Barricade Location, Height and Length

CHAPTER 6
ELECTRICAL STANDARDS

A. GENERAL

The National Electrical Code, published by the National Fire Protection Association as NFPA 70 (reference (j)), does not address specifically explosives; however, Article 500 of the Code, Hazardous (Classified) Locations, does establish standards for the design and installation of electrical equipment and wiring in atmospheres containing combustible dusts and flammable vapors and gasses that, in general, are comparably hazardous. Exceptions are extraordinarily hazardous explosives, such as nitroglycerin, that require special consideration, including physical isolation from electric motors, devices, lighting fixtures, and the like. National Electrical Code standards and this Chapter are minimum requirements for DoD buildings and areas containing explosives.

B. HAZARDOUS LOCATIONS

National Electrical Code definitions of Class I, Division 1, and Class II, Division 1, hazardous locations are modified as follows for DoD explosives applications:

1. Areas containing explosives dusts or explosives that may through handling produce dust capable of being dispersed in the atmosphere shall be regarded as Class II, Division 1, hazardous locations.

2. Areas in which explosives sublimation or condensation may occur shall be regarded as both Class I, Division 1, and Class II, Division 1, hazardous locations.

C. SPECIAL OCCUPANCIES

1. To ensure assignment to the proper hazardous locations class and group, it is necessary to have knowledge of the properties of explosives involved. Minimum requirements include sensitivity to heat and spark and thermal stability. If the properties of an explosive are such that Class I or Class II, or both, provide inadequate protection under prevailing conditions, use of any of the following approaches is acceptable: intrinsically safe equipment, purged or pressurized and suitably temperature-limited equipment, exclusion of electrical equipment from the hazardous atmosphere, or isolation of equipment from the hazardous atmosphere by means of dust, vapor, or gas-free enclosures with surface temperatures positively maintained at safe levels.

2. Underground Storage Facilities. All wiring and electrical equipment in underground storage facilities must, in addition to any other requirements of this chapter, be of moisture and corrosion resistant materials and construction unless a site specific analysis indicates that such construction is not necessary. Underground facilities must have emergency lighting systems to provide minimum illumination in the event of a power failure.

7. Commanders will develop evacuation plans for their installations that reference the appropriate withdrawal distances as part of the disaster response plan. The Commander is responsible for alerting civilian authorities of any imminent explosive accident on the installation that may affect the local community and for providing these authorities with the appropriate emergency withdrawal distances.

8. Ammunition containing both explosives and chemical agents (see Table 8-1) requires special attention and precautions in firefighting. Fires involving such ammunition shall be fought in accordance with their fire division characteristics, but responding personnel must also take into account the potential additional hazards and precautions discussed in Chapter 11 relating to the effects of the chemical agents involved.

9. Entry to underground storage facilities following a fire or explosion requires special precautions. Monitoring for the presence of toxic fumes, oxygen depleted atmospheres and structural damage shall be performed during initial entry following an accident. Commanders will develop written procedures that define actions to be taken in such emergency situations.

G. UNDERGROUND STORAGE

1. Scope

a. This section details Q-D standards for the underground storage of military ammunition and explosives. Underground storage includes natural caverns and below grade, excavated chambers, but criteria of this section also apply to any storage facility providing the overpressure confinement effects typically encountered in underground storage. Use criteria of this section only when the minimum distance from the perimeter of a storage area to an exterior surface exceeds $0.25 \cdot W^{1/3}$. Otherwise use aboveground siting criteria. This minimum distance most often, but not always, equals the thickness of the earth cover. This section addresses explosives safety criteria both with and without rupture of the earth cover.

b. Expected ground shock, debris, and airblast hazards from an accidental explosion in an underground storage facility depend on several variables, including the local geology and site specific parameters. These parameters vary significantly from facility to facility, so criteria listed here will likely be safety conservative for some geologies and configurations. Siting distances other than those listed may be used when validated by approved experimental or analytical results showing equivalent protection to that required. Default, approved methods for establishing Q-D are discussed below.

c. Q-D siting requirements of this section may be determined from the applicable equations or by interpolating between the table and figure entries.

d. The provisions of this section do not apply to storage in earth-covered magazines described in Chapter 5 of this Standard.

2. Design of Underground Storage Facilities.

a. Underground storage facilities may consist of a single chamber or a series of connected chambers. There may also be other protective construction features in the facility. The chamber(s) may be either excavated or natural geological cavities. Figure 9-3 illustrates general concepts for several possible configurations of underground facilities.

b. Design of new underground storage facilities must take into account site conditions, storage requirements and operational needs. Once these are established, a design may be developed based on Corps of Engineers definitive drawing number DEF 421-80-04.

c. An underground storage site normally requires designed protection against lightning only for exposed or partially exposed parts. Metal and structural parts of the site that have less than 2 feet (60 cm) of earth cover shall be protected as for an aboveground site (see Chapter 7). Lightning protection requirements must be considered on a site specific basis.

3. Explosion Effects in Underground Storage Sites

a. Confinement caused by the very limited space in underground storage will cause very high pressures of prolonged duration from an accidental explosion. Blast waves and dynamic flow fields will travel at high velocity throughout the underground facility. Ground shocks will be produced, and break-up of the earth cover with attendant debris throw may occur.

b. Under conditions of heavy confinement and high loading density Hazard Division 1.3 material may, while either detonating or burning, produce intense gas pressures sufficient to rupture the earth cover and create a significant debris hazard.

c. An accidental explosion involving only Hazard Division 1.2 material will likely start a fire that is sustained by burning packages and other ammunition. This may cause further explosions that become more frequent as the fires build and multiply until everything in the site is destroyed. Results of these repeated explosions will depend on the type and quantity of munitions, the type of explosion produced, and the layout of the facility. Hazards created outside the underground facility will likely not be as severe as those produced by Hazard Division 1.1 or 1.3 material.

4. Protection Provided. Quantity distance criteria listed here provide separation distances from stored ammunition and explosives to mitigate the hazards caused by ground shock, debris, or air blast. The required distance for a given quantity and storage condition is that corresponding to the dominant (farthest-reaching) hazard that is applicable to the exposure under consideration. It is therefore the largest of the distances determined to be necessary for protection against the individual effects considered in turn.

5. Chamber Separation Requirements

a. Minimum storage chamber separation distances are required to prevent or control the communication of explosions or fires between donor and acceptor chambers. There are three modes by which an explosion or fire can be communicated: by rock spall, by propagation through cracks or fissures, and by airblast or thermal effects traveling through connecting passages.

b. Prevention of Damage by Rock Spall (Hazard Divisions 1.1 and 1.3). The chamber separation distance is the shortest distance (rock thickness) between two chambers. When an explosion occurs in a donor chamber, a shock wave is transmitted through the surrounding rock. The intensity of the shock decreases with distance. For small chamber separation distances, the shock may be strong enough to produce spalling of the rock walls of acceptor chambers. Spalled rock of sufficient mass, traveling with a sufficient velocity, may damage or sympathetically detonate impacted munitions in the acceptor chambers. When no

specific protective construction is used, the minimum chamber separation distance, D_{cd} required to prevent hazardous spall effects is:

$$D_{cd}=2.5 \cdot W^{1/3} \qquad (9\text{-}1)$$

Where D_{cd} is in feet and W is in pounds. D_{cd}, in no case, shall be less than 15 feet.

The separation distances defined above applies to chamber loading densities up to 3.0 pounds per cubic foot, as determined from Table 9-20, and moderately strong to strong rock types. This loading density is the basis for values of D_{cd} listed in Table 9-21. For greater loading densities in moderately strong to strong rock, the required separation distance is:

$$D_{cd}=5.0 \cdot W^{1/3} \qquad (9\text{-}2)$$

For weak rock, at all loading densities, the separation distance is:

$$D_{cd}=3.5 \cdot W^{1/3} \qquad (9\text{-}3)$$

c. Prevention of Propagation by Rock Spall (Hazard Divisions 1.1 and 1.3). If damage to stored munitions in the adjacent chambers is acceptable, the chamber separation distance can be reduced to the distance required to prevent propagation of the detonation by the impact of rock spall against the munitions. This is considered an immediate mode of propagation because time separations between donor and acceptor explosions may not be sufficient to prevent coalescence of blastwaves. Unless analyses or experiments indicate otherwise, explosives weights subject to this mode must be added to other donor explosives weights to determine NEW. When no special protective construction is used, the separation distance, D_{cp}, to prevent explosion communication by spalled rock is:

$$D_{cp} = 1.5 \cdot W^{1/3} \qquad (9\text{-}4)$$

Where D_{cp} is in feet and W is in pounds

When the acceptor chamber has protective construction to prevent spall and collapse (into the acceptor chamber) the separation distance to prevent propagation by impact of spalled rock is:

$$D_{cp} = 0.75 \cdot W^{1/3} \qquad (9\text{-}5)$$

D_{cp} is in feet and W is the weight in pounds of Hazard Divisions 1.1 and 1.3 material in the donor chamber. Separation distances, D_{cp} and D_{cd}, are listed in Table 9-21. These distances are based on an explosive loading density of about 17 lb/ft^3. The distances will likely be safety conservative for lower loading densities but the effects have not been quantified.

d. Prevention of Propagation through Cracks and Fissures (Hazard Divisions 1.1 and 1.3). Propagation between a donor and acceptor chamber has been observed to occur when natural, near horizontal jointing planes, cracks or fissures in the rock between the chambers are opened by the lifting force of the detonation pressure in the donor chamber. Prior to construction of a multichamber magazine, a careful site investigation must be made to ensure that such joints or fissures do not extend from one chamber location to an adjacent one. Should such defects be encountered during facility excavation, a reevaluation of the intended siting will be required.

e. Prevention of Propagation Through Passageways (Hazard Divisions 1.1 and 1.3). Flame and hot gas may cause delayed propagation. Time separations between the original donor event and the potential explosions of this mode will likely be sufficient to prevent coalescence of blastwaves. Consequently, for purposes of Q-D siting, only the maximum credible explosives weight need be used to determine NEW. In order to protect assets, blast and fire resistant doors must be installed within multi-chambered facilities. . Evaluations for required chamber separations due to this communication mode should be made on a site specific basis using procedures outlined in Corps of Engineers definitive drawing DEF 421-80-04.

f. For Hazard Divisions 1.1 and 1.3 materials, chamber entrances at the ground surface, or entrances to branch tunnels off the same side of a main passageway, shall be separated by at least 15 feet. Entrances to branch tunnels off opposite sides of a main passageway shall be separated by at least twice the width of the main passageway.

g. Chambers, containing only Hazard Divisions 1.2 and 1.4 material and separated by the appropriate distance listed above, may be used to the limits of their physical capacities except any items having special stacking and NEW restrictions. However, when Hazard Division 1.2 or 1.4 material is stored in the same chamber with Hazard Division 1.1 or 1.3 material, the propellant and explosive content of all hazard divisions material shall be added to obtain NEW.

6. Critical Chamber Cover Thickness. The chamber cover thickness is the shortest distance between the natural rock surface at the chamber ceiling (or in some cases, a chamber wall) and the ground surface. The critical cover thickness required to prevent breaching of the chamber cover by a detonation is $2.5 \cdot W^{1/3}$ for all types of rock.

7. External Q-D Determinations.

a. Hazard Division Material Dependence

(1) Hazard Division 1.1 and 1.3 Materials. Distances shall be determined from the total quantity of explosives, propellants, pyrotechnics, and incendiary materials in the individual chambers, unless the total quantity is subdivided to prevent rapid communication of an incident from one subdivision to

another (see subsection B.1. of Chapter 9). All Hazard Divisions 1.1 and/or 1.3 material subject to involvement in a single incident shall be assumed to contribute to the explosion yield as would an equal weight of TNT. Any significant and validated differences in energy release per unit mass of the compositions involved from that of TNT may be considered. A connected chamber or cavern storage site containing Hazard Division 1.1 or 1.3 material shall be treated as a single chamber site, unless explosion communication is prevented by adequate subdivision or chamber separation.

(2) Hazard Division 1.2 Materials. Except for primary fragments from openings to underground storage, external explosives safety hazards are not normally significant for Hazard Division 1.2 materials. The safe distance for both IBD and PTR is the IBD distance in Tables 9-6 through 9-9 for locations within $\pm$10 degrees of the centerline of a tunnel opening. These default criteria apply only to those detonations which occur where a line-of-sight path exists from the detonation point to any portion of the tunnel opening. For detonations which do not have a line-of-sight path to the tunnel opening, or where the line-of-sight path is intercepted by a barricade beyond the opening, the IBD and PTR hazard distances are zero.

(3) Hazard Division 1.4 Materials. External explosives safety hazards are not normally significant for Hazard Division 1.4 materials. Accordingly, external Q-D criteria do not apply for Hazard Division 1.4 materials.

b. Q-D Reference Points

(1) Distances determined by blast or debris issuing from tunnel openings shall be the minimum distance measured from the openings to the nearest wall or point of the location to be protected. Use extended centerlines of the openings as reference lines for directional effects.

(2) Distances determined for airblast and debris produced by breaching of the chamber cover shall be the minimum distance from an exterior point defined by chamber cover thickness, on the ground surface above the storage chamber to the nearest wall or point of the location to be protected. For configurations where the storage chambers are not distinct from the access tunnel, the distance is the shortest distance from the tunnel roof directly above the charge to the surface.

(3) Distances determined for ground shock shall be the minimum distance measured from the nearest wall of the storage chamber to the location to be protected.

c. Inhabited Building Distance (Hazard Divisions 1.1 and 1.3 Materials). Inhabited building distances shall be the largest of those distances required for protection against ground shock, debris, and airblast as defined below.

(1) Ground Shock

(a) For protection of residential buildings against significant structural damage by ground shock, the maximum particle velocity induced in the ground at the building site may not exceed the following values, which form the basis for the equations in Paragraph (b), below:

2.4 ips in soil

4.5 ips in weak rock,

9.0 ips in strong rock.

(b) For sitings in moderately strong to strong rock with chamber loading densities of 3.0 lbs/ft^3 or less, the IBD for ground shock, D_{ig} is:

$$D_{ig} = 5.8 \cdot W^{1/3} \qquad \text{(9-6a)}$$

Where D_{ig} is in feet and W is the explosive quantity in pounds.

For higher loading densities in chambers sited in moderately strong to strong rock, and for all loading densities in other materials, the IBD for ground shock is:

$$D_{ig} = 12.5 \cdot f_g \cdot W^{4/9} \quad \text{(Moderately strong to strong rock)} \qquad \text{(9-6b)}$$

$$D_{ig} = 11.1 \cdot f_g \cdot W^{4/9} \quad \text{(Weak rock)} \qquad \text{(9-6c)}$$

$$D_{ig} = 2.1 \cdot f_g \cdot W^{4/9} \quad \text{(Soil)} \qquad \text{(9-6d)}$$

Values of D_{ig}/f_g are shown in Table 9-22. The dimensionless, decoupling factor, f_g depends on chamber loading density, w, and is:

$$f_g = (4/15) \cdot w^{0.3}. \qquad \text{(9-7)}$$

Values of f_g are shown in Table 9-23. Chamber loading density is the NEW (in pounds) divided by the volume of the storage chamber, V_c (in cubic feet), and is provided in Table 9-20. Alternate values for D_{ig} may be used only when justified by site specific ground shock data.

(2) Debris

(a) A minimum IBD distance of 1800 feet (550 meters) for debris throw from an opening shall apply within $\pm$10 degrees to either side of the centerline axis of that opening unless positive means are used to prevent or control the debris throw.

(b) Distances required for protection of inhabited areas against the effects of debris D_{id} thrown from breaching of the cover material over a detonation depend on the thickness of the cover, C, over the storage chamber. Siting criteria for debris from a surface breach need not be considered for chamber cover thicknesses greater than the critical value, C_c, of $2.5 \cdot W^{1/3}$. If the cover thickness is less than C_c, the distance, D_{id}, will be calculated from $D_{id} = f_d \cdot f_c \cdot W^{0.41}$, where $f_d = 0.6 \cdot w^{0.18}$, and f_c is a constant related to the type of rock around the storage chamber.

(c) Values of D_{id}/f_d, for moderately strong to strong rock and for weak rock, are listed in Tables 9-24 and 9-25. Values of f_c are shown graphically in Figure 9-4. Values for the decoupling factors f_g and f_d are listed in Table 9-23.

(d) Special features may be incorporated in the design of underground facilities to reduce the IBD for debris ejected through tunnel openings.

(i) Debris Traps are pockets excavated in the rock at or beyond the end of sections of tunnel, designed to catch debris from a storage chamber detonation. Debris traps should be at least 20 percent wider and 10 percent taller than the tunnel leading to the trap, with a depth measured along the shortest wall of at least one tunnel diameter.

(ii) Expansion chambers are large rooms located between the storage chamber(s) and the tunnel entrance(s), having a cross-section area at least three times as great as that of the largest tunnel intersecting the expansion chamber, and a length that is at least as great as the expansion chamber width. Expansion chambers are very effective in entrapping debris, as long as the tunnels entering and exiting the chambers are either offset in axial alignment by at least two tunnel widths, or enter and exit the chambers in directions that differ by at least 45 degrees.

(iii) Portal Barricades provide a means of reducing IBD from debris by obstructing the path of the debris as it exits the tunnel. Construction and location requirements for barricades are contained in paragraph C.5. of Chapter 5.

(iv) High-pressure Closures are large blocks constructed of concrete or other materials, that can obstruct or greatly reduce the flow of blast effects and debris from an explosion, from or into a storage chamber. For chamber loading densities of about 0.625 lb/ft^3 or above, closure blocks will contain 40 percent or more of the explosion debris within the detonation chamber, provided that the block is designed to remain intact. If a closure block fails under the blast load, it will produce a volume of debris in addition to that from the chamber itself. However, since the block's mass and inertia are sufficient to greatly reduce the velocity of the primary debris, the effectiveness of other debris-mitigating features, such as debris traps, expansion chambers, and barricades is increased.

(e) Debris traps, and expansion chambers intended to entrap debris, must be designed to contain the full potential volume of debris, based on the maximum capacity of the largest storage chamber. Design specifications for debris traps, expansion chambers, closure blocks and portal barricades are given in Corps of Engineers definitive drawing number DEF 421-80-04.

(f.) Use of barricades in conjunction with any other of these features will lower the debris hazard to a level where Q-D considerations for debris will not be required.

(3) <u>Airblast</u>

(a) An explosion in an underground storage chamber may produce external airblast from two sources; the exit of blast from existing openings (tunnel entrances, ventilation shafts, etc.) and the rupture or breach of the chamber cover by the detonation. Required inhabited building distances are to be independently determined for each of these airblast sources, with the maximum IBD used for siting. If the chamber cover thickness is less than the critical thickness, C_c, given in paragraph 6., some amount of external airblast will be produced, depending on the cover thickness. Use the following procedure to find IBD for airblast produced by breaching of the chamber cover

$C \leq 0.25 \cdot W^{1/3}$:	Use IBD for surface burst of bare explosives charge Table 9-1 (Note 3)
$0.25 \cdot W^{1/3} < C \leq 0.50 \cdot W^{1/3}$:	Use 1/2 of IBD for surface burst of bare explosives charge
$0.50 \cdot W^{1/3} < C \leq 0.75 \cdot W^{1/3}$:	Use 1/4 of IBD for surface burst of bare explosives charge
$0.75 \cdot W^{1/3} < C$:	Airblast hazards from blast through the earth cover are negligible relative to ground shock or debris hazards.

(b) Overpressure and debris hazards must be determined for each facility opening whose cross-section area is five percent or more of that of the largest opening.

(c) Distance vs overpressure along the centerline axis of a single opening is:

$$R = 149.3 \cdot D \cdot [(W/V_E)^{0.5}/p_{SO}]^{1/1.4} \qquad (9\text{-}8a)$$

where:

R: distance from opening (feet).

D: effective hydraulic diameter that controls dynamic flow issuing from the opening (feet). [Compute D as $D = 4 \cdot A/P$, where A is the minimum cross-sectional area of the tunnel that is located within five tunnel diameters of the opening, and P is the tunnel perimeter.]

P_{SO}: overpressure at distance R (psi).

W: maximum credible event (MCE) in pounds.

V_E: Total volume engulfed by the blast wavefront within the tunnel system at the time the wavefront arrives at the point of interest (ft^3).

(d) Distance vs overpressure off the centerline axis of the opening is:

$$R(\Pi) = R(\Pi=0)/(1 + (\Pi/56)^2)^{1/1.4} \qquad (9\text{-}8b)$$

where:

$R(\Pi=0)$ is the distance along the centerline axis, and

Π is the horizontal angle from the centerline (degrees).

(e) Equations 9-8a and 9-8b show that the distance providing protection from an overpressure exceeding P_{SO} depends on the hydraulic diameter, and the angle from centerline axis for the location of interest. Figure 9-5 shows the ratio of off-axis to on-axis distances.

(f) Find required IBD for airblast using the appropriate equations discussed above, with the criteria that the total incident overpressure at IBD shall not exceed:

$$P_{SO} = 1.2 \text{ psi for } W < 100{,}000 \text{ lbs}, \qquad (9\text{-}9a)$$

$$P_{SO} = 44.57 \cdot W^{-0.314} \text{ psi for } 100{,}000 \leq W \leq 250{,}000 \text{ lbs} \qquad (9\text{-}9b)$$

$$P_{SO} = 0.9 \text{ psi for } W > 250{,}000 \text{ lbs}. \qquad (9\text{-}9c)$$

(g) For the overpressures specified in equations 9-9a to 9-9c, on-axis IBD distances are:

$$R = 131.1 \cdot D \cdot (W/V_E)^{1/2.8} \text{ for } W < 100{,}000 \text{ lbs}, \qquad (9\text{-}10a)$$

$$R = 9.91 \cdot D \cdot W^{0.581} / V_E^{0.357} \quad \text{for } 100{,}000 \leq W \leq 250{,}000 \text{ lbs} \qquad (9\text{-}10b)$$

$$R = 161.0 \cdot D (W/V_E)^{1/2.8} \quad \text{for} \quad W > 250{,}000 \text{ lbs} \qquad (9\text{-}10c)$$

(h) Q-D distances for IBD for airblast may be determined from the equations listed above or from entries in Table 9-26 and 9-27.

(4) Airblast Mitigation Methods for Reducing IBD. Special features may be incorporated in underground storage facility designs to reduce external airblast. Table 9-26 provides IBD data for underground facilities with as well as without some of these features. Proven elements that may be incorporated in underground storage facilities to reduce the airblast IBD include:

(a) Facility Layouts. A single-chamber facility with a straight access tunnel leading from the chamber to the portal is commonly called a "shotgun" magazine because the blast and debris are channeled to the external area as if fired from a long-barreled gun. More complex facility layouts will provide some reductions in the exit pressures due to reflections of the explosive shock against the tunnel walls. The cumulative effect is to reduce the overpressure at the shock front to the point that the peak overpressure is produced by the detonation gas flow following the front. The detonation gas pressure decreases as the volume it occupies increases. Therefore, the peak overpressure produced at the tunnel opening will also decrease with an increase in the total volume of the tunnels and chambers that can be filled by the blast as it travels from the detonation source (e.g., a storage chamber) to the opening, as given in the previous section. Larger facilities will, therefore, produce greater reductions in the effective overpressure at the opening, which will, in turn, reduce the IBD. The IBD should be reduced by 10 percent when two or more openings of similar cross-sectional area exist.

(b) Expansion Chambers. Expansion chambers are so-named because of the volume they provide for the expansion of the detonation gasses behind the shock front as it enters the chamber from a connecting tunnel. Some additional degradation of the peak pressure at the shock front occurs as the front expands into the chamber and reflects from the walls. The principal benefit provided by an expansion chamber, however, is simply the added volume which decreases pressures. Expansion chambers also have practical purposes. They may be used as loading/unloading chambers, providing weather protection for the transfer of munitions from trucks to materials handling equipment prior to placement in storage chambers, or as turn-around areas for transport vehicles servicing facilities through a single entry passage.

(c) Constrictions. Constrictions are short lengths of tunnel whose cross sectional areas are reduced to one-half or less of the normal tunnel cross section. The use of constrictions should be limited to locations within 5 tunnel diameters of the tunnel exit or to the entrances of storage chambers. A constriction near the tunnel exit, where the overpressure has dropped near a minimum value in the tunnel, defines the hydraulic diameter to be used in Equation 9-8a. The purpose

the tunnel, defines the hydraulic diameter to be used in Equation 9-8a. The purpose of a constriction at a chamber entrance is to reduce the intrusion of airblast and thermal effects into the chamber from a detonation in an adjacent chamber. A constricted chamber entrance also reduces the area, and hence the total loading on a blast door installed to protect the chamber contents.

(d) Portal Barricades. For most underground storage facilities, the airblast from a storage chamber detonation that exits a tunnel portal will be in the form of a shock wave. It will expand in all directions from the portal in a manner similar to that from a detonation at the portal. A barricade in front of the portal will reflect that portion of the shock wave moving directly outward from the portal. By reflecting this portion of the total airblast, the pressures along the extended tunnel axis are reduced, and the pressures in the opposite direction, behind the portal are increased. The result is a more circular IBD area centered at the portal. Since much of the blast is also reflected upward, the total IBD area is less than would occur without a barricade. For cases where the blast must travel a large distance from the storage chamber to the portal, with several changes in direction along the travel path, the airblast exiting the portal may primarily consist of a strong, highly-directional gas flow. A barricade will intercept such a flow and deflect it in directions 90 degrees from the tunnel axis. Whether the blast exiting the portal is shock or gas flow-dominated, the barricade must be located within certain minimum and maximum standoff distances to be effective. For the barricade design recommended in paragraph C.5. of Chapter 5, these limits are one to three tunnel diameters (at the portal). Portal barricades reduce the IBD along the extended tunnel axis by 50 percent. The total IBD area is only slightly reduced, but will change to a circular area, half of which is behind the portal. The barricade should be constructed as described in paragraph 5.C.5 and Corps of Engineers definitive drawing number DEF 421-80-04.

(e) High-pressure Closures

(i) High Pressure Closures are large blocks constructed of concrete or other materials, that can obstruct or greatly reduce the flow of blast effects and debris from an explosion, from or into a storage chamber. If used to provide complete protection to the contents of a chamber from an explosion in another chamber, the block must be designed to move from a normally-closed position to an open position to allow entry into the chamber. Blast doors are not required for this type of closure block. If used to reduce Q-D by restricting the blast outflow from a chamber, the block must be designed to be rapidly driven from an open to a closed position by the detonation pressures in the chamber. While this type of block will provide some protection of chamber contents from an explosion in another chamber, blast doors must also be used to provide complete protection. Tests have shown that a closure block with sufficient mass can obstruct the initial outflow of airblast from an explosion in a chamber to reduce pressures in the connecting tunnels by a factor of two or more, even when the block is destroyed. Blocks with sufficient strength to remain structurally intact can provide greater

reductions. Since many variables influence the performance of a closing device, their design details must be developed on a site-specific basis.

(ii) A 50% reduction in IBD should be applied to a high pressure closure block provided that the block is designed to remain intact in the event of an explosion. This reduction is applicable for loading densities of 0.625 lb/ft^3 or higher., but greater than 0.0625 lb/ft^3, reductions may be calculated by the formula:

$$y(\%) = 50 \cdot \log_{10}(16.02 \cdot w) \qquad (9\text{-}11)$$

where y is the percent reduction in IBD, and w is loading density in lb/ft^3. For loading densities lower than 0.0625 lb/ft^3, y = 0.

Closure block design criteria are found in Corps of Engineers definitive design drawing number DEF 421-80-04.

d. Public Traffic Route (PTR) Distance (Hazard Divisions 1.1 and 1.3 Materials)

(1) Ground Shock. Q-D is 60 percent of IBD for ground shock.

(2) Debris. Q-D is 60 percent of IBD for debris.

(3) Airblast. Q-D is 60 percent of IBD for airblast.

e. Intraline Distance (Hazard Divisions 1.1 and 1.3 Materials)

(1) Ground Shock. Q-D criteria for ground shock do not apply.

(2) Debris. For locations within ±10 degrees of the centerline of a tunnel opening, site intraline facilities at IBD for debris issuing from the opening, calculated as directed in paragraph 9.G.7.c.(2). Q-D criteria for debris are not applicable for locations greater than ±10 degrees from the centerline axis of an opening.

(3) Airblast. Overpressure at barricaded and unbarricaded intraline distances shall not exceed 12 and 3.5 psi, respectively.

f. Distance to Aboveground Magazines (Hazard Divisions 1.1 and 1.3 Materials)

(1) Ground Shock. Q-D criteria for ground shock do not apply.

(2) Debris. For locations within ±10 degrees of the centerline of an opening, site aboveground magazines at IBD for debris issuing from the opening,

IAW Chapter 9, paragraph G.7.c.(2). Q-D criteria for debris from rupture of the chamber cover do not apply.

(3) Airblast. Overpressure at barricaded and unbarricaded above-ground magazine distance shall not exceed 27 and 8 psi, respectively.

g. Distance to Earth-Covered Aboveground Magazines (Hazard Divisions 1.1 and 1.3 Materials)

(1) Ground Shock. Q-D criteria for ground shock do not apply.

(2) Debris. Q-D criteria for debris from rupture of the chamber cover do not apply. Q-D criteria for debris issuing from an opening do not apply if the magazine is oriented for side-on or rear-on exposures to the debris but the criteria do apply for frontal exposures. Site earth-covered magazines that are located within ± 10 degrees of the centerline of an opening and oriented for a frontal debris exposure at IBD for that debris hazard calculated as directed in Chapter 9, paragraph G.7.c.(2).

(3) Airblast. These sitings are based on the strength of the ECM under consideration and utilize side-on overpressures calculated from Equations 9-8a and 9-8b.

(a) Head-on Exposure:

(I) 7-Bar ECM: Site where the side-on overpressure, p_{so}, is 29 psi.

(ii) 3-Bar ECM: Site where the side-on overpressure, p_{so}, is 16 psi.

(iii) Undefined ECM: Site where the side-on overpressure, p_{so}, is 3.5 psi.

(b) Other than Head-on Exposure: Site all ECMs where side-on overpressure, p_{so}, is 45 psi.

Table 9-20. Chamber Loading Density (w)

NEW (lbs)	Chamber Volume (ft^3)							
	2,000	5,000	10,000	20,000	30,000	50,000	75,000	100,000
1,000	0.500	0.200	0.100	0.050	0.033	0.020	0.013	0.010
1,200	0.600	0.240	0.120	0.060	0.040	0.024	0.016	0.012
1,400	0.700	0.280	0.140	0.070	0.047	0.028	0.019	0.014
1,600	0.800	0.320	0.160	0.080	0.053	0.032	0.021	0.016
1,800	0.900	0.360	0.180	0.090	0.060	0.036	0.024	0.018
2,000	1.000	0.400	0.200	0.100	0.067	0.040	0.027	0.020
2,500	1.250	0.500	0.250	0.125	0.083	0.050	0.033	0.025
3,000	1.500	0.600	0.300	0.150	0.100	0.060	0.040	0.030
3,500	1.750	0.700	0.350	0.175	0.117	0.070	0.047	0.035
4,000	2.000	0.800	0.400	0.200	0.133	0.080	0.053	0.040
5,000	2.500	1.000	0.500	0.250	0.167	0.100	0.067	0.050
6,000	3.000	1.200	0.600	0.300	0.200	0.120	0.080	0.060
7,000	3.500	1.400	0.700	0.350	0.233	0.140	0.093	0.070
8,000	4.000	1.600	0.800	0.400	0.267	0.160	0.107	0.080
9,000	4.500	1.800	0.900	0.450	0.300	0.180	0.120	0.090
10,000	5.000	2.000	1.000	0.500	0.333	0.200	0.133	0.100
12,000	6.000	2.400	1.200	0.600	0.400	0.240	0.160	0.120
14,000	7.000	2.800	1.400	0.700	0.467	0.280	0.187	0.140
16,000	8.000	3.200	1.600	0.800	0.533	0.320	0.213	0.160
18,000	9.000	3.600	1.800	0.900	0.600	0.360	0.240	0.180
20,000	10.000	4.000	2.000	1.000	0.667	0.400	0.267	0.200
25,000	12.500	5.000	2.500	1.250	0.833	0.500	0.333	0.250
30,000	15.000	6.000	3.000	1.500	1.000	0.600	0.400	0.300
35,000	17.500	7.000	3.500	1.750	1.167	0.700	0.467	0.350
40,000	20.000	8.000	4.000	2.000	1.333	0.800	0.533	0.400
45,000	22.500	9.000	4.500	2.250	1.500	0.900	0.600	0.450
50,000	25.000	10.000	5.000	2.500	1.667	1.000	0.667	0.500
60,000	30.000	12.000	6.000	3.000	2.000	1.200	0.800	0.600
70,000	35.000	14.000	7.000	3.500	2.333	1.400	0.933	0.700
80,000	40.000	16.000	8.000	4.000	2.667	1.600	1.067	0.800
90,000	45.000	18.000	9.000	4.500	3.000	1.800	1.200	0.900
100,000	50.000	20.000	10.000	5.000	3.333	2.000	1.333	1.000
120,000	60.000	24.000	12.000	6.000	4.000	2.400	1.600	1.200
140,000	70.000	28.000	14.000	7.000	4.667	2.800	1.867	1.400
160,000	80.000	32.000	16.000	8.000	5.333	3.200	2.133	1.600
180,000	90.000	36.000	18.000	9.000	6.000	3.600	2.400	1.800
200,000	100.000	40.000	20.000	10.000	6.667	4.000	2.667	2.000
300,000	150.000	60.000	30.000	15.000	10.000	6.000	4.000	3.000
400,000	200.000	80.000	40.000	20.000	13.333	8.000	5.333	4.000
500,000	250.000	100.000	50.000	25.000	16.667	10.000	6.667	5.000
600,000	300.000	120.000	60.000	30.000	20.000	12.000	8.000	6.000
700,000	350.000	140.000	70.000	35.000	23.333	14.000	9.333	7.000
800,000	400.000	160.000	80.000	40.000	26.667	16.000	10.667	8.000
900,000	450.000	180.000	90.000	45.000	30.000	18.000	12.000	9.000
1,000,000	500.000	200.000	100.000	50.000	33.333	20.000	13.333	10.000

Table 9-21. Chamber Separation

Weight (lbs)	D_{cp} (ft)	D_{cd} (ft)		
	$1.5 \cdot W^{1/3}$	$2.5 \cdot W^{1/3}$	$3.5 \cdot W^{1/3}$	$5.0 \cdot W^{1/3}$
1,000	15	25	35	50
1,200	16	27	37	53
1,400	17	28	39	56
1,600	17.5	30	41	58
1,800	18	31	43	61
2,000	19	32	44	63
2,500	20.4	34	48	68
3,000	22	36	50	72
3,500	23	38	53	76
4,000	24	40	56	79
4,500	25	42	58	83
5,000	26	43	60	85
6,000	27	46	64	91
7,000	29	48	67	96
8,000	30	50	70	100
9,000	31	52	73	104
10,000	33	54	76	108
12,000	34	58	80	114
14,000	36	61	84	121
16,000	38	63	88	126
18,000	39	66	92	131
20,000	41	68	95	136
25,000	44	74	102	146
30,000	47	78	109	155
35,000	49	82	114	164
40,000	51	86	120	171
45,000	53	89	124	178
50,000	55	93	129	184
60,000	59	98	137	196
70,000	62	103	144	206
80,000	65	108	151	215
90,000	67	112	157	224
100,000	70	116	162	232
120,000	74	124	173	247
140,000	78	130	182	260
160,000	81	136	190	271
180,000	85	142	198	282
200,000	88	147	205	292
250,000	94	158	220	315
300,000	100	168	234	335
350,000	106	177	247	352
400,000	111	185	258	368
450,000	115	192	268	383
500,000	119	199	278	397
600,000	127	211	295	422
700,000	133	222	311	444
800,000	139	232	325	464
900,000	145	242	338	483
1,000,000	150	250	350	500

Table 9-22. Distance to Protect Against Ground Shock

Weight(lbs)	$2.1W^{4/9}$	D_{ig}/f_g $11.1W^{4/9}$	$12.5W^{4/9}$	D_{ig} $5.8W^{1/3}$
1,000	45	239	269	58
1,200	49	259	292	62
1,400	53	278	313	65
1,600	56	295	332	68
1,800	59	311	350	71
2,000	62	325	366	73
2,500	68	359	405	79
3,000	74	390	439	84
3,500	79	417	470	88
4,000	84	443	499	92
4,500	88	467	525	96
5,000	93	489	551	99
6,000	100	530	597	105
7,000	107	568	640	111
8,000	114	603	679	116
9,000	120	635	715	121
10,000	126	665	749	125
12,000	137	722	813	133
14,000	146	773	870	140
16,000	155	820	923	146
18,000	163	864	973	152
20,000	171	906	1,020	157
25,000	189	1,000	1,126	170
30,000	205	1,084	1,221	180
35,000	220	1,161	1,308	190
40,000	233	1,232	1,388	198
45,000	246	1,298	1,462	206
50,000	257	1,361	1,532	214
60,000	279	1,476	1,662	227
70,000	299	1,580	1,779	239
80,000	317	1,677	1,888	250
90,000	334	1,767	1,990	260
100,000	350	1,852	2,085	269
120,000	380	2,008	2,261	286
140,000	407	2,150	2,421	301
160,000	432	2,282	2,570	315
180,000	455	2,404	2,708	327
200,000	477	2,520	2,837	339
250,000	526	2,782	3,133	365
300,000	571	3,017	3,398	388
350,000	611	3,231	3,639	409
400,000	649	3,429	3,861	427
450,000	684	3,613	4,069	444
500,000	716	3,786	4,264	460
600,000	777	4,106	4,624	489
700,000	832	4,397	4,951	515
800,000	883	4,666	5,254	538
900,000	930	4,916	5,537	560

Table 9-23. Functions of Loading Density

Loading Density w (lbs/ft^3)	Ground Shock f_g ($0.267\ w^{0.30}$)	Debris f_d ($0.600\ w^{0.18}$)
1.0	0.27	0.60
1.2	0.28	0.62
1.4	0.30	0.64
1.6	0.31	0.65
1.8	0.32	0.67
2.0	0.33	0.68
2.5	0.35	0.71
3.0	0.37	0.73
3.5	0.39	0.75
4.0	0.40	0.77
4.5	0.42	0.79
5.0	0.43	0.80
6.0	0.46	0.83
7.0	0.48	0.85
8.0	0.50	0.87
9.0	0.52	0.89
10.0	0.53	0.91
12.0	0.56	0.94
14.0	0.59	0.96
16.0	0.61	0.99
18.0	0.64	1.01
20.0	0.66	1.03
25.0	0.70	1.07
30.0	0.74	1.11
35.0	0.78	1.14
40.0	0.81	1.17
45.0	0.84	1.19
50.0	0.86	1.21
60.0	0.91	1.25
70.0	0.96	1.29
80.0	0.99	1.32
90.0	1.03	1.35
100.0	1.06	1.37

Table 9-24. Distances to Protect Against Hard Rock Debris

	$C/W^{1/3}$ ($ft/lb^{1/3}$)							
	0.3	0.5	0.7	0.9	1.1	1.6	2.1	3
Weight (lbs)	D_{id}/f_d (ft							
1000	163	180	200	205	195	145	92	62
1200	170	195	215	220	210	155	98	67
1400	185	210	230	235	225	165	105	72
1600	195	220	240	250	240	175	110	76
1800	205	230	250	260	250	180	115	79
2000	210	240	260	270	260	190	120	83
2500	230	260	290	300	290	210	135	91
3000	250	290	310	320	310	225	145	98
3500	270	300	330	340	330	240	155	105
4000	280	320	350	360	350	250	160	110
4500	300	340	370	380	360	260	170	115
5000	310	350	380	400	380	280	175	120
6000	330	380	410	430	410	300	190	130
7000	350	400	440	460	440	320	205	140
8000	370	430	470	480	460	330	215	145
9000	390	450	490	500	480	350	225	155
10000	410	470	520	520	500	370	235	160
12000	440	500	560	560	540	400	250	175
14000	470	540	580	600	580	420	270	185
16000	500	560	620	640	620	440	290	195
18000	520	600	640	680	640	470	300	205
20000	540	620	680	700	680	490	310	215
25000	600	680	740	760	740	540	340	235
30000	640	740	800	820	800	580	370	250
35000	680	780	860	880	840	620	390	270
40000	720	820	900	940	900	640	420	285
45000	760	860	940	980	940	680	440	295
50000	800	900	980	1000	980	700	460	310
60000	860	980	1050	1100	1050	760	490	335
70000	920	1050	1150	1150	1100	820	520	355
80000	960	1100	1200	1250	1100	860	560	375
90000	1000	1150	1250	1300	1250	900	580	395
100000	1050	1200	1300	1350	1300	940	600	410
120000	1150	1300	1400	1450	1400	1000	660	445
140000	1200	1400	1500	1550	1500	1100	700	475
160000	1300	1450	1600	1650	1600	1150	740	500
180000	1350	1550	1650	1750	1650	1200	780	525
200000	1400	1600	1750	1800	1750	1250	800	550
250000	1550	1750	1900	2000	1900	1350	880	600
300000	1650	1900	2050	2150	1500	1500	960	645
350000	1750	2000	2200	2250	2200	1600	1000	690
400000	1850	2100	2300	2400	2300	1650	1050	725
450000	1950	2200	2450	2500	2400	1750	1100	765
500000	2050	2300	2500	2600	2500	1800	1150	800
600000	2200	2500	2700	2800	2700	1950	1250	860
700000	2350	2700	2900	3000	2900	2100	1350	915
800000	2450	2800	3100	3200	3100	2200	1400	965
900000	2600	3000	3200	3300	3200	2300	1500	1015

Table 9-25. Distances to Protect Against Soft Rock Debris

	$C/W^{1/3}$ ($ft/lb^{1/3}$)							
	0.2	0.6	0.75	0.9	1	1.5	1.75	2.5
Weight (lbs)	D_{id}/f_d (ft)							
1,000	165	200	207	198	184	91	62	30
1,200	177	216	223	213	199	98	67	32
1,400	189	230	238	227	212	105	72	34
1,600	200	243	251	240	224	110	76	36
1,800	210	255	264	252	235	116	79	38
2,000	219	266	275	263	245	121	83	40
2,500	240	292	302	288	268	133	91	43
3,000	258	314	325	311	289	143	98	47
3,500	275	335	346	331	308	152	104	50
4,000	291	354	366	350	326	161	110	53
4,500	305	371	384	367	342	169	116	55
5,000	319	388	401	383	357	176	121	58
6,000	343	418	432	413	384	190	130	62
7,000	366	445	460	440	409	202	139	66
8,000	386	470	486	464	433	214	147	70
9,000	405	493	510	487	454	224	154	74
10,000	423	515	532	509	474	234	161	77
12,000	456	555	574	548	511	252	173	83
14,000	486	591	611	584	544	269	184	88
16,000	513	624	645	617	575	284	195	93
18,000	539	655	677	648	603	298	204	98
20,000	562	684	707	676	630	311	213	102
25,000	616	750	775	741	690	341	234	112
30,000	664	808	835	798	744	367	252	120
35,000	707	861	890	851	792	391	268	128
40,000	747	909	940	898	837	413	283	136
45,000	784	954	986	943	878	434	297	142
50,000	819	996	1,030	985	917	453	311	148
60,000	882	1,074	1,110	1,061	988	488	335	160
70,000	940	1,144	1,182	1,130	1,053	520	357	170
80,000	993	1,208	1,249	1,194	1,112	549	377	180
90,000	1,042	1,268	1,311	1,253	1,167	576	395	189
100,000	1,088	1,324	1,368	1,308	1,218	602	413	197
120,000	1,172	1,426	1,475	1,410	1,313	648	445	213
140,000	1,249	1,520	1,571	1,502	1,399	691	474	226
160,000	1,319	1,605	1,659	1,586	1,477	730	500	239
180,000	1,384	1,684	1,741	1,665	1,550	766	525	251
200,000	1,445	1,759	1,818	1,738	1,619	800	548	262
250,000	1,584	1,927	1,992	1,905	1,774	876	601	287
300,000	1,707	2,077	2,147	2,052	1,911	944	648	310
350,000	1,818	2,212	2,287	2,186	2,036	1,006	690	330
400,000	1,921	2,337	2,416	2,309	2,151	1,062	729	348
450,000	2,016	2,453	2,535	2,424	2,257	1,115	765	366
500,000	2,105	2,561	2,647	2,531	2,357	1,164	798	382
600,000	2,268	2,760	2,853	2,727	2,540	1,254	860	411
700,000	2,416	2,940	3,039	2,905	2,705	1,336	917	438
800,000	2,552	3,105	3,210	3,068	2,858	1,412	968	463
900,000	2,678	3,259	3,369	3,220	2,999	1,481	1,016	486

Table 9-26. Values for Ratio, $D_{HYD}/V_E^{1/2.8}$

	$D_{HYD}/V_E^{1/2.8}$					
V_E (ft^3)	Effective Hydraulic Diameter, D_{HYD} (ft)					
	10	15	20	25	30	35
1,000	0.8483	1.2725	1.6967	2.1209	2.5450	2.9692
2,000	0.6623	0.9935	1.3246	1.6558	1.9869	2.3181
3,000	0.5730	0.8595	1.1460	1.4326	1.7191	2.0056
4,000	0.5171	0.7756	1.0341	1.2927	1.5512	1.8097
5,000	0.4775	0.7162	0.9549	1.1937	1.4324	1.6711
6,000	0.4474	0.6710	0.8947	1.1184	1.3421	1.5658
7,000	0.4234	0.6351	0.8468	1.0585	1.2702	1.4819
8,000	0.4037	0.6055	0.8074	1.0092	1.2110	1.4129
9,000	0.3871	0.5806	0.7741	0.9676	1.1612	1.3547
10,000	0.3728	0.5591	0.7455	0.9319	1.1183	1.3047
20,000	0.2910	0.4365	0.5820	0.7275	0.8731	1.0186
30,000	0.2518	0.3777	0.5036	0.6295	0.7554	0.8812
40,000	0.2272	0.3408	0.4544	0.5680	0.6816	0.7952
50,000	0.2098	0.3147	0.4196	0.5245	0.6294	0.7343
60,000	0.1966	0.2949	0.3931	0.4914	0.5897	0.6880
70,000	0.1860	0.2791	0.3721	0.4651	0.5581	0.6511
80,000	0.1774	0.2661	0.3548	0.4434	0.5321	0.6208
90,000	0.1701	0.2551	0.3401	0.4252	0.5102	0.5952
100,000	0.1638	0.2457	0.3276	0.4095	0.4914	0.5733
200,000	0.1279	0.1918	0.2557	0.3197	0.3836	0.4476
300,000	0.1106	0.1660	0.2213	0.2766	0.3319	0.3872
400,000	0.0998	0.1497	0.1997	0.2496	0.2995	0.3494
500,000	0.0922	0.1383	0.1844	0.2305	0.2766	0.3226
600,000	0.0864	0.1296	0.1727	0.2159	0.2591	0.3023
700,000	0.0817	0.1226	0.1635	0.2044	0.2452	0.2861
800,000	0.0779	0.1169	0.1559	0.1948	0.2338	0.2728
900,000	0.0747	0.1121	0.1495	0.1868	0.2242	0.2615
1,000,000	0.0720	0.1080	0.1439	0.1799	0.2159	0.2519
2,000,000	0.0562	0.0843	0.1124	0.1405	0.1686	0.1967
3,000,000	0.0486	0.0729	0.0972	0.1215	0.1458	0.1701
4,000,000	0.0439	0.0658	0.0877	0.1097	0.1316	0.1535
5,000,000	0.0405	0.0608	0.0810	0.1013	0.1215	0.1418

Table 9-27. Scaled IBD for Airblast without Mitigating Devices[1,2,3]

	$r(1)/(D_{HYD}/V_E^{1/2.8})$					
NEW	Horizontal Angle from Centerline Axis (Degrees)					
(lbs)	0	30	60	90	120	180
1,000	1,545	1,290	895	621	452	273
2,000	1,979	1,653	1,146	795	579	349
3,000	2,287	1,910	1,325	919	669	404
4,000	2,535	2,117	1,468	1,019	741	448
5,000	2,745	2,292	1,590	1,103	803	485
7,000	3,096	2,585	1,793	1,244	905	547
10,000	3,516	2,936	2,037	1,413	1,028	621
20,000	4,504	3,761	2,609	1,810	1,317	795
30,000	5,206	4,347	3,015	2,092	1,522	919
40,000	5,769	4,818	3,341	2,319	1,687	1,019
50,000	6,247	5,217	3,619	2,511	1,827	1,103
70,000	7,045	5,883	4,081	2,831	2,060	1,244
100,000	8,002	6,683	4,635	3,216	2,340	1,413
200,000	11,977	10,002	6,937	4,813	3,502	2,115
250,000	13,633	11,384	7,896	5,479	3,987	2,407
500,000	17,462	14,582	10,114	7,018	5,106	3,083
700,000	19,691	16,444	11,406	7,914	5,759	3,477
1,000,000	22,367	18,678	12,955	8,989	6,541	3,949
2,000,000	28,649	23,925	16,594	11,514	8,378	5,059
3,000,000	33,113	27,652	19,180	13,308	9,684	5,847
5,000,000	39,740	33,187	23,018	15,972	11,622	7,017
7,000,000	44,815	37,424	25,957	18,011	13,106	7,913
10,000,000	50,903	42,509	29,484	20,458	14,886	8,988

[1]IBD for airblast without airblast mitigating devices:

$$r(1)/(D_{HYD}/V_E^{1/1.4}) = 149.3 \cdot \{W^{0.5}/[p_{SO} \cdot (1+(1/56)^2)]\}^{1/1.4} \quad \text{(English Units)}$$

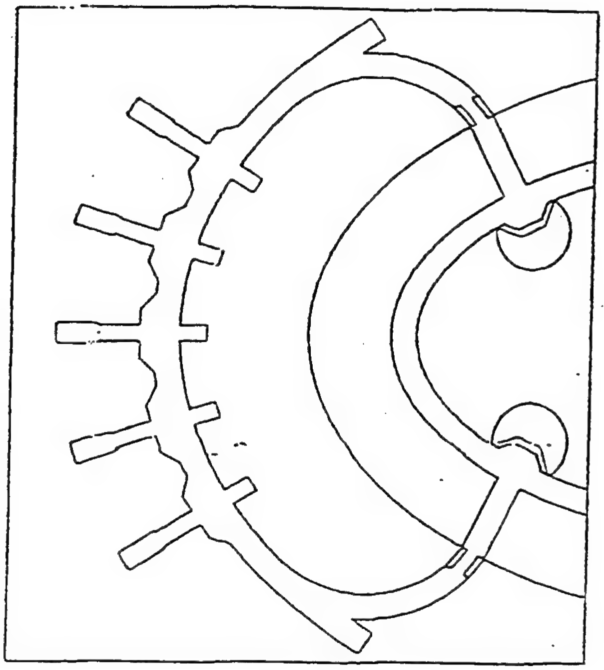
where:

	$p_{SO} = 1.2$ psi	$W \le 100{,}000$ lbs
	$p_{SO} = 44.57 \cdot W^{-0.314}$ psi	$100{,}000 < W \le 250{,}000$ lbs
	$p_{SO} = 0.9$ psi	$W > 250{,}000$ lbs

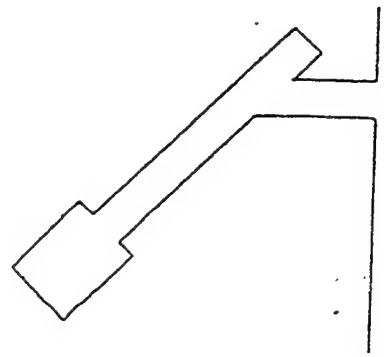
[2]Reduce IBD by 50% when portal barricade configured IAW COE Definitive Drawing 421-80-04 is used.

[3]Reduce IBD as follows when a closure plug designed IAW COE Definitive Drawing 421-80-04 is used:

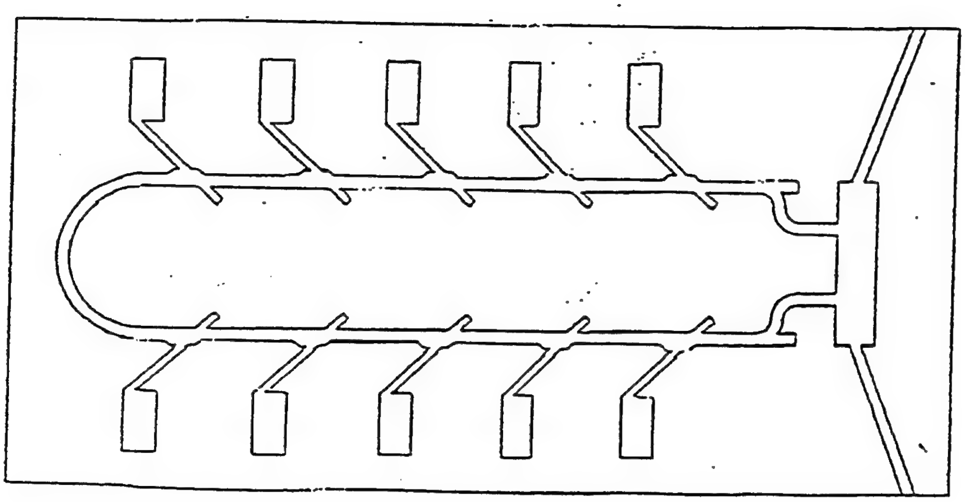
Reduction (%) = 0%	$w \le 0.0625$ lb/ft^3
Reduction (%) = $50 \log_{10}(16.02 \cdot w)$	$0.0625 < w \le 0.625$ lb/ft^3
Reduction (%) = 50%	$w > 0.625$ lb/ft^3



b. Medium facility
1,000 to 10,000 kg (NEQ) per chamber



c. Small facility
≤ 1,000 kg (NEQ) facility



a. Large facility
10,000 to 100,000 kg (NEQ) per chamber

Figure 9-3. TYPICAL UNDERGROUND FACILITIES

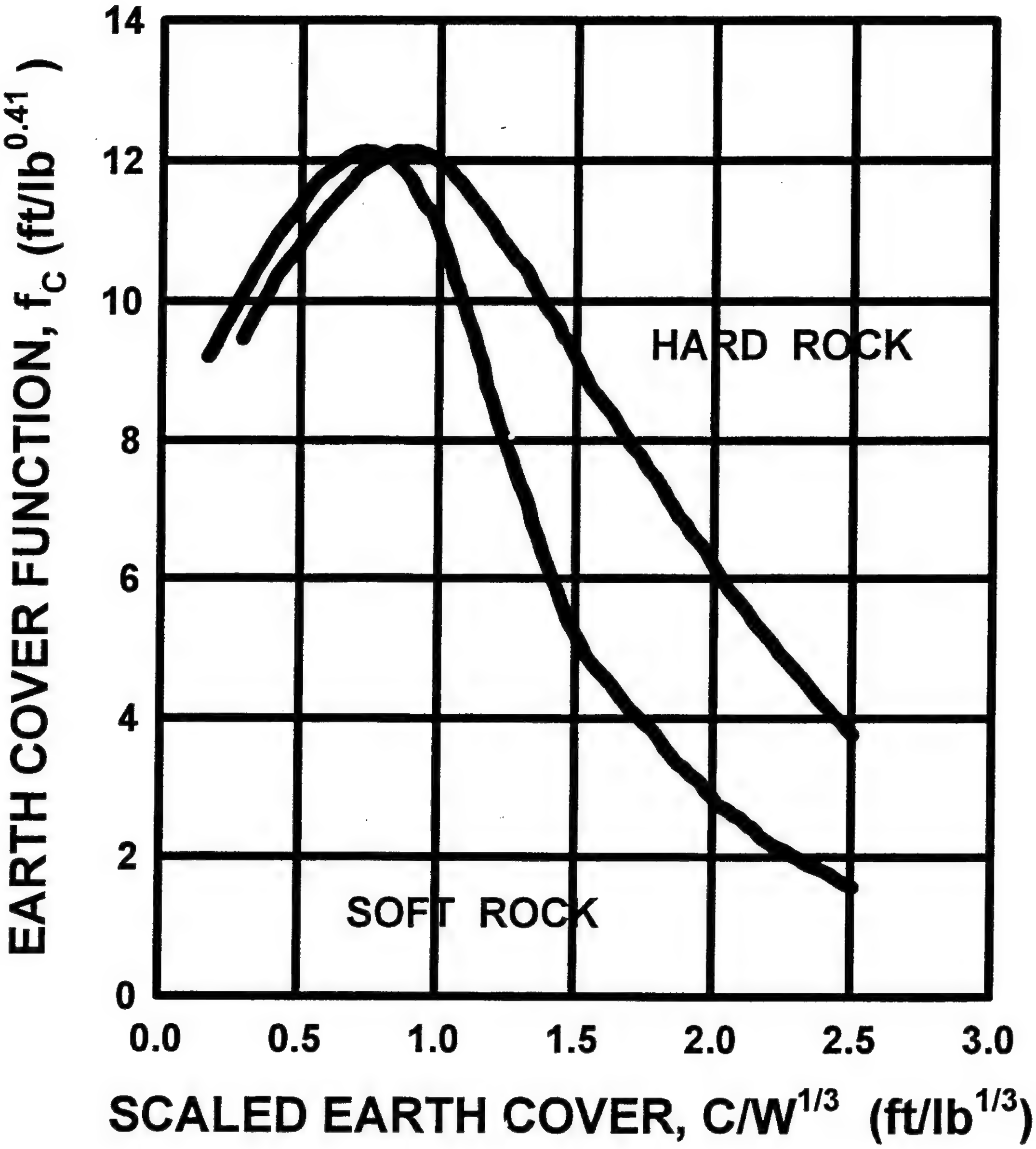


Figure 9-4. Debris Dispersal Functions

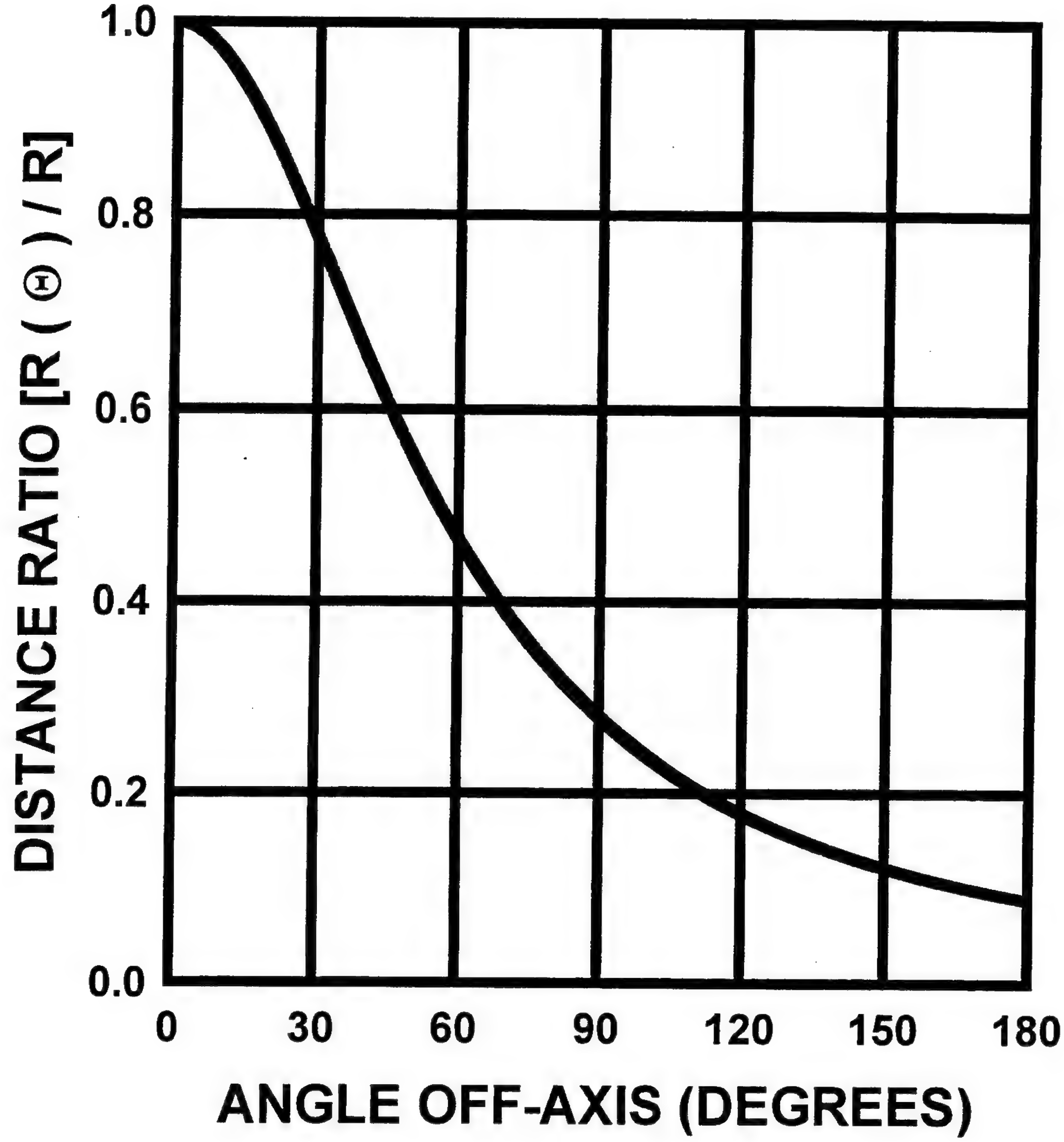


Figure 9-5. Constant Pressure Contour

APPENDIX A

GLOSSARY

Explanation of Terms. The following are descriptions of terms and phrases commonly used in conjunction with ammunition, explosives, and other dangerous materials. These are listed to provide a degree of uniformity of description in the use of technical information throughout these standards:

1. Aboveground Magazines. Any type of magazine abovegrade other than standard or nonstandard earth-covered types of magazines.

2. Action Level. One-half of the exposure limit for a chemical agent averaged over an 8-hour work shift.

3. Administration Area. The area in which are located administrative buildings that function for the installation as a whole, excluding those offices located near and directly serving components of explosives storage and operating areas.

4. Aircraft Passenger Transport Operations. Passenger transport operations for the purpose of applying explosives Q-D tables are defined as follows: Passenger transport traffic involving military dependents and civilians other than those employed by or working directly for DoD Components. The following are not considered passenger transport operations.

a. Infrequent flights of base and command administrative aircraft that may, on occasion, provide some space available travel to authorized personnel.

b. Travel of direct hire appropriated funds personnel employed by any DoD Component.

c. Travel of such personnel as contractor and technical representatives traveling to or from direct support assignments at DoD installations.

6. Ammunition and Explosives. Includes (but is not necessarily limited to) all items of ammunition; propellants, liquid and solid; high and low explosives; guided missiles; warheads; devices; pyrotechnics; chemical agents; and components and substances associated therewith, presenting real or potential hazards to life and property.

7. Ammunition and Explosives Aircraft Cargo Area. Any area specifically designated for:

a. Aircraft loading or unloading of transportation configured ammunition and explosives.

b. Parking aircraft loaded with transportation configured ammunition and explosives.

8. Ammunition and Explosives Area. An area specifically designated and set aside from other portions of an installation for the development, manufacture, testing, maintenance, storage, or handling of ammunition and explosives.

9. Anchorages

a. Scuttling Site. An area of water specifically designated for positioning a ship for its flooding or sinking under emergency situations.

b. Explosives Anchorage. An area of water specifically designated for loading and unloading vessels and for anchoring vessels carrying a cargo of ammunition and explosives.

10. Auxiliary Building. Any building accessory to or maintained and operated to serve an operating building, line, plant, or pier area. Explosive materials are not present in an auxiliary building, such as powerplants and change houses, paint and solvent lockers, and similar facilities.

11. Barricade. An intervening barrier, natural or artificial, of such type, size, and construction as to limit in a prescribed manner the effect of an explosion on nearby buildings or exposures.

12. Blast Impulse. The product of the overpressure from the blast wave of an explosion and the time during which it acts at a given point (that is, the area under the positive phase of the overpressure-time curve).

13. Blast Overpressure. The pressure, exceeding the ambient pressure, manifested in the shock wave of an explosion.

14. Cavern Storage Site. A natural cavern or former mining excavation adapted for the storage of ammunition and explosives.

15. Ceiling Value. The concentration of chemical agent that may not be exceeded for any period of time.

16. Chamber Storage Site. An excavated chamber or series of excavated chambers especially suited to the storage of ammunition an explosives. A cavern may be subdivided or otherwise structurally modified for use as a chamber storage site.

18. Chemical Agent. A substance that is intended for military use with lethal or incapacitating effects upon personnel through its chemical properties. Excluded from chemical agents for purposes of this Standard are riot control agents, chemical

herbicides, smoke- and flame-producing items, and individual dissociated components of chemical agent ammunition.

19. Classification Yard. A railroad yard used for receiving, dispatching, classifying, and switching of cars.

19a. Closure Block. A protective construction feature designed to seal the entrance tunnel to an underground storage chamber in the event of an explosion within the chamber. MAGAE blocks are passive closures that are driven by the blast from a normally open to a closed position. KLOTZ blocks are active closures, operated by a hydraulic system to move from a normally closed to an open position (for access).

20. Combat Aircraft Parking Area. Any area specifically designated for:

a. Aircraft loading or unloading of combat-configured munitions.

b. Parking aircraft loaded with combat-configured munitions.

21. Compatibility. Ammunition or explosives are considered compatible if they may be stored or transported together without increasing significantly either the probability of an accident or, for a given quantity, the magnitude of the effects of such an accident.

22. Connected-Chamber Storage Site. A chamber storage site consisting of two or more chambers connected by ducts or passageways. Such chambers may be at the ends of branch tunnels off a main passageway.

23. Controlling Authority. The headquarters of the DoD Component concerned.

23a. Debris. Any solid particle thrown by an explosion or other strong energetic reaction. For aboveground detonations, debris usually refers to secondary fragments. For underground storage facilities, debris refers to both primary and secondary fragments, which are transported by a strong flow of detonation gasses.

23b. Debris Trap. A protective construction feature in an underground storage facility which is designed to capture fragments and debris from a detonation within the facility. This is usually accomplished by using the inertia of the material to separate it from the detonation gas stream. (Illustrated in Figure 9-3)

24. Deflagration. A rapid chemical reaction in which the output of heat is enough to enable the reaction to proceed and be accelerated without input of heat from another source. Deflagration is a surface phenomenon with the reaction products flowing away from the unreacted material along the surface at subsonic velocity. The effect of a true deflagration under confinement is an explosion. Confinement of the reaction increases pressure, rate of reaction and temperature, and may cause transition into a detonation.

25. Detonation. A violent chemical reaction within a chemical compound or mechanical mixture evolving heat and pressure. A detonation is a reaction which proceeds through the reacted material toward the unreacted material at a super- sonic velocity. The result of the chemical reaction is exertion of extremely high pressure on the surrounding medium forming a propagating shock wave that originally is of supersonic velocity. A detonation, when the material is located on or near the surface of the ground, is characterized normally by a crater.

26. Dividing Wall. A wall designed to prevent, control, or delay propagation of an explosion between quantities of explosives on opposite sides of the wall.

27. DoD Mishap. An unplanned event or series of events that result in damage to DoD property, occupational illness to DoD military or civilian personnel, injury to DoD military personnel on or off duty, injury to on-duty civilian personnel; damage to public and private property, or injury and illness to non-DoD personnel as a result of DoD operations.

28. Dolphin. A mooring post or posts on a wharf or quay.

28a. Donor/Acceptor. A total quantity of stored ammunition may be subdivided into separate storage units in order to reduce the MCE, and, consequently, the Q-D of an accidental detonation. The separation distances, with or without an intervening barrier, should be sufficient to ensure that a detonation does not propagate from one unit to another. For convenience the storage unit which detonates Is termed the donor, and nearby units, which may be endangered, are termed acceptors. The locations of the donor and acceptor define the PES and ES, respectively.

29. Engineering Controls. Regulation of facility operations through the use of prudent engineering principles, such as facility design, operation sequencing, equipment selection, and process limitations.

29a. Expansion Chamber. A protective construction feature in an underground storage facility which is designed to reduce the blast shock and overpressure exiting the facility by increasing the total volume of the complex. It may also function as an operating area within the underground facility, as well as a debris trap. (Illustrated in Figure 9-3)

30. Explosion. A chemical reaction of any chemical compound or mechanical mixture that, when initiated, undergoes a very rapid combustion or decomposition releasing large volumes of highly heated gases that exert pressure on the surrounding medium. Also, a mechanical reaction in which failure of the container causes the sudden release of pressure from within a pressure vessel, for example, pressure rupture of a steam boiler. Depending on the rate of energy release, an explosion can be categorized as a deflagration, a detonation, or pressure rupture.

31. Explosives Facility. Any structure or location containing ammunition and explosives excluding combat aircraft parking areas or ammunition and explosives aircraft cargo areas.

32. Exposed Site (ES). A location exposed to the potential hazardous effects (blast, fragments, debris, and heat flux) from an explosion at a potential explosion site (PES). The distance to a PES and the level of protection required for an ES determine the quantity of ammunition or explosives permitted in a PES.

33. Firebrand. A projected burning or hot fragment whose thermal energy is transferred to a receptor.

34. Fragmentation. The breaking up of the confining material of a chemical compound or mechanical mixture when an explosion takes place. Fragments may be complete items, subassemblies, pieces thereof, or pieces of equipment or buildings containing the items.

35. Hazardous Fragment. A hazardous fragment is one having an impact energy of 58 ft-lb or greater.

36. Hazardous Fragment Density. A density of hazardous fragments exceeding one per 600 sq. ft.

37. High Explosive Equivalent or Explosive Equivalent. The amount of a standard explosive that, when detonated, will produce a blast effect comparable to that which results at the same distances from the detonation or explosion of a given amount of the material or which performance is being evaluated. It usually is expressed as a percentage of the total net weight of all reactive materials contained in the item or system. For the purpose of these standards, TNT is used for comparison.

38. Holding Yard. A location for groups of railcars, trucks, or trailers used to hold ammunition, explosives, and dangerous materials for interim periods before storage or shipment.

39. Hygroscopic. A tendency of material to absorb moisture from its surroundings.

40. Hypergolic. A property of various combinations of chemical to self ignite upon contact with each other without a spark or other external initiation.

41. Inhabited Buildings. Buildings or structures, other than operating buildings occupied in whole or in part by human beings, both within and outside DoD establishments. They include but are not limited to schools, churches, residences (quarters), service clubs, aircraft passenger terminals, stores, shops, factories, hospitals, theaters, mess halls, post offices, and post exchanges.

42. Inspection Station. A designated location at which trucks and railcars containing ammunition and explosives are inspected.

43. Interchange Yard. An area set aside for the exchange of railroad cars or vehicles between the common carrier and DoD activities.

44. Intraline Distance. The distance to be maintained between any two operating buildings and sites within an operating line, of which at least one contains or is designed to contain explosives, except that the distance from a service magazine for the line to the nearest operating building may be not less than the intraline distance required for the quantity of explosives contained in the service magazine.

45. Joint DoD - Non-DoD Use Runway/Taxiway. A runway and/or taxiway serving both DoD and commercial aircraft. A runway and/or taxiway serving solely DoD, chartered, or Non-DoD aircraft on DoD authorized business is not joint use.

46. Launch Pads. The load-bearing base, apron, or platform upon which a rocket, missile, or space vehicle and its launcher rest during launching.

47. Liquid Propellants. Substances in fluid form (including cryogenics) used for propulsion or operating power for missiles, rockets, ammunition and other related devices (See Table 9-16). For purposes of this standard, liquid fuels and oxidizers are considered propellants even when stored and handled separately.

47a. Loading Density. Quantity of explosive per unit volume, usually expressed in pounds per cubic foot (lbs/ft^3). As applied to underground storage facilities, there are two types of loading densities used in Q-D calculations:

(1) Chamber loading density is based on the NEW within an individual storage chamber and the volume of the chamber (V_{CH}).

(2) The calculation of airblast peak pressures and IBD's for explosions in underground storage facilities is based on the shock-engulfed volume (V_E) of the facility. This is the total volume filled by the expanding gases at the time the blast front reaches the point of interest (e.g., the entrance to an adjacent chamber). It includes volumes in any direction that the gases can enter, to a distance from the explosion source that equals the distance from the source to the point of interest. For IBD, the point of interest is the tunnel opening.

48. Loading Docks. Facilities, structures, or paved areas, designed and installed for transferring ammunition and explosives between any two modes of transportation.

49. Lunchrooms. Facilities where food is prepared or brought for distribution by food service personnel. It may serve more than one PES. A breakroom in an operating building may be used by personnel assigned to the PES to eat meals.

50. Magazine. Any building or structure, except an operating building, used for the storage of ammunition and explosives.

51. Magazine, Earth-Covered, Nonstandard. All earth-covered magazines except those listed in subsection B.1., Chapter 5 with earth covering equal to or greater than that required by standard igloo magazines.

52. Mass-Detonating Explosives. HE, black powder, certain propellants, certain pyrotechnics, and other similar explosives, alone or in combination, or loaded into various types of ammunition or containers, most of the entire quantity of which can be expected to explode virtually instantaneously when a small portion is subjected to fire, to severe concussion or impact, to the impulse of an initiating agent, or to the effect of a considerable discharge of energy from without. Such an explosion normally will cause severe structural damage to adjacent objects. Explosion propagation may occur immediately to other items of ammunition and explosives stored sufficiently close to and not adequately protected from the initially exploding pile with a time interval short enough so that two or more quantities must be considered as one for Q-D purposes.

53. Maximum Credible Event (MCE)

a. General. In hazards evaluation, the MCE from a hypothesized accidental explosion, fire, or agent release is the worst single event that is likely to occur from a given quantity and disposition of ammunition and explosives. The event must be realistic with a reasonable probability of occurrence considering the explosion propagation, burning rate characteristics, and physical protection given to the items involved. The MCE evaluated on this basis may then be used as a basis for effects calculations and casualty predictions.

b. Chemical Agent. An MCE for a chemical agent is defined as the hypothesized maximum quantity of agent that could be released from an ammunition item (without explosives), bulk container, or process as a result of a single unintended, unplanned, or accidental occurrence. It must be realistic with a reasonable probability of occurrence.

54. Navigable Streams. Those parts of streams, channels, or canals capable of being used in their ordinary or maintained condition as highways of commerce over which trade and travel are or may be conducted in the customary modes, not including streams that are not capable of navigation by barges, tugboats, and other large vessels unless they are used extensively and regularly for the operation of pleasure boats.

55. NEQ. Net explosive quantity expressed in kilograms.

56. NEW. Net explosive weight expressed in pounds.

57. Nitrogen Padding (or Blanket). Used to fill the void or ullage of a closed container with nitrogen gas to prevent oxidation of the chemical contained therein and

to avoid formation of a flammable mixture, or to maintain a nitrogen atmosphere in or around an operation or piece of equipment.

58. Non-DoD Components. Any entity (government, private, or corporate) that is not a part of the Department of Defense.

59. Operating Building. Any structure, except a magazine, in which operations pertaining to manufacturing, processing, handling, loading, or assembling of ammunition and explosives are performed.

60. Operating Line. A group of buildings, facilities, or related work stations so arranged as to permit performance of the consecutive steps in the manufacture of an explosive, or in the loading, assembly, modification, and maintenance of ammunition.

61. Operational Shield. A barrier constructed at a particular location or around a particular machine or operating station to protect personnel, material, or equipment from the effects of a possible localized fire or explosion.

62. Passenger Railroad. Any steam, diesel, electric, or other railroad which carries passengers for hire.

63. PEL. The maximum time-weighted average airborne concentration (milligrams per cubic meter) of a chemical agent to which it is believed that essentially all members of a specific population can be exposed for a specific period without adverse effect.

64. PES. The location of a quantity of explosives that will create a blast, fragment, thermal, or debris hazard in the event of an accidental explosion of its contents. Quantity limits for ammunition and explosives at a PES are determined by the distance to an ES.

65. Pier. A landing place or platform built into the water, perpendicular or oblique to the shore, for the berthing of vessels.

66. Prohibited Area. A specifically designated area at airfields, seadromes, or heliports in which all ammunition and explosives facilities are prohibited.

67. Public Access Exclusion Distance. The distance arc (calculated) from the agent source at which no more than 10.0, 4.3, and 150 milligrams per minute per cubic meter is present for GB, VX, and mustard, respectively.

68. Public Traffic Route. Any public street, road, highway, navigable stream, or passenger railroad (includes roads on a military reservation that are used routinely by the general public for through traffic).

69. Q-D. The quantity of explosive material and distance separation relationships that provide defined types of protection. These relationships are based on levels of risk considered acceptable for the stipulated exposures and are tabulated in the appropriate Q-D tables. Separation distances are not absolute safe distances but are relative protective or safe distances. Greater distances than those shown in the tables shall be used whenever practicable.

70. Quay. A marginal wharf or solid fill.

70a. Robust Munitions. These are munitions having a ratio of the explosive weight to empty case weight less than 1.00 and a nominal wall thickness of at least one (1) cm. Examples of robust ammunition includes MK 80 series bombs, M107 projectiles, Tomahawk and Harpoon penetration warheads and 20, 25, and 30 mm cartridges. Examples of non-robust ammunition include CBU's, torpedo warheads, underwater mines, and TOW and HELLFIRE, Sparrow and Sidewinder missiles. Unless otherwise noted, all air-to-air missile warheads are defined as non-robust, regardless of this ratio.

70b. Rock Strength. Strong, moderately strong, and weak rock are designators which provide a general classification of rock types for siting underground storage facilities for ground shock hazards. Classification of a rock body into one of these three rankings is based on the rock impedance factor:

$$\text{rock impedance factor} = \rho \cdot c \cdot 10^{-6}$$

and

$$\rho = \gamma / g$$

where
- γ is the rock density, lbs/ft^3
- g is the gravitational force, ft/sec^2
- ρ is the mass density of the rock, lbs-sec^2/ft^4
- c is the seismic velocity of the rock, ft/sec

The rock impedance factor will be 0.75 or more for strong rock; between 0.75 and 0.5 for moderately strong rock; and less than 0.5 for weak rock.

Values of these parameters can usually be estimated based on examinations of exposed rock outcrops or core samples from an exploratory drill hole. For the detailed design of an underground storage facility (maximum span width, rock reinforcement, etc.), standard engineering classification systems for rock should be used.

71. Runway. Any surface on land designated for aircraft takeoff and landing operations, or a designated lane of water for takeoff and landing operations of seaplanes.

72. Service Magazine. A building of an operating line used for the intermediate storage of explosives materials.

73. Ship or Barge Units. All explosives within a line encompassing the ship or barge being loaded, the space on the pier for spotting of freight cars and trucks, and the space in the water for barges which may be working the ship or barge.

74. Single-Chamber Storage Site. An excavated chamber with its own access to the natural ground surface, not connected to any other storage chamber.

75. Source Emission Limits. The amount of chemical agent that may be released at a particular point that allows for natural dilution, ventilation, and meteorological conditions interfacing.

75a. Spall. Spall refers to pieces of a material (and the process by which they are formed) that are broken loose from the surface of a parent body by tensile forces that are created when a compression shock wave travels through the body and reflects from the surface. For undeground storage, spall normally refers to the rock broken loose from the wall of an acceptor chamber by the shock wave transmitted through the rock from an explosion in a nearby donor chamber.

76. Standard Igloo Magazine. An earth-covered, arch-type magazine, with or without a separate door barricade, constructed according to an approved standard drawing identified in subsection B.1. of Chapter 5.

77. Static Test Stand. Locations on which liquid propellant engines or solid propellent motors are tested in place.

78. Support Facilities. Ammunition and explosives storage or operations that support solely the functions of tactical or using units as distinguished from storage depots or manufacturing facilities.

79. Suspect Truck and Car Site. A designated location for placing trucks and railcars containing ammunition or explosives that are suspected of being in a hazardous condition. These sites also are used for trucks and railcars that may be in a condition that is hazardous to their contents.

80. Tactical Facilities. Tactical facilities are prepared locations with an assigned combat mission, such as missile launch facilities, alert aircraft parking areas, or fixed gun positions.

81. Taxiway or Taxilane. Any surface designated as such in the basic airfield clearance criteria specified by a DoD Component publication or Federal Aviation Regulation (reference (n)).

82. Toxic Area. A defined area in which SCG K ammunition or Class 6 chemical agents are handled or stored.

83. Unit Risk. The risk to personnel and/or facilities that is associated with debris, fragment and/or blast hazards that is the result of the detonation of a single round of ammunition.

84. Wharf. A landing place or platform built into the water or along the shore for the berthing of vessels.

85. Wharf Yard. A yard that is close to piers or wharves in which railcars or trucks are held for short periods of time before delivery to the piers or wharves.

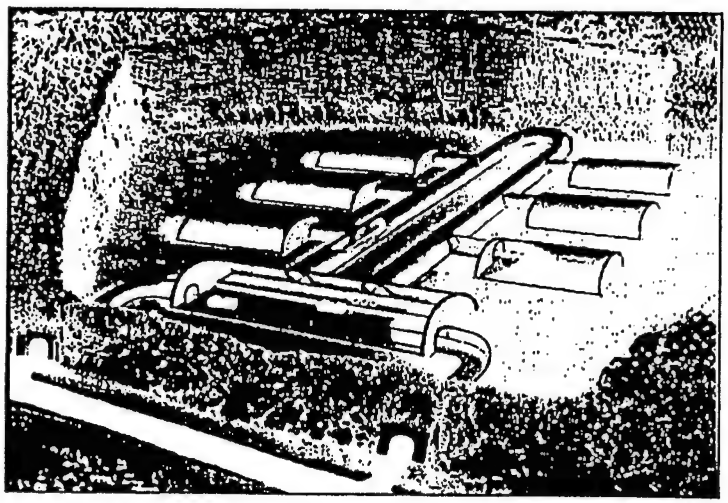
APPENDIX B

DEFINITIVE DESIGN DRAWINGS AND SPECIFICATIONS

(Reduced from the originals)

US Army Corps
of Engineers
Engineering and Support
Center, Huntsville

DEFINITIVE DRAWINGS
UNDERGROUND AMMUNITION
STORAGE FACILITY



DRAWING INDEX				
SHEET. REF NO.	DESIGN FILE NO.	REVISION		SHEET TITLE
		REV. NO.	AM/CO	
----	83061			COVER AND INDEX SHEET
G-1	83062			GENERAL NOTES
G-2	83063			GENERAL NOTES
G-3	83064			GENERAL NOTES
G-4	83065			ROCK CLASSIFICATION TABLES
----	83066			NOT USED
S-1	83067			LARGE FACILITY LAYOUT
S-2	83068			SMALL FACILITY LAYOUT
S-3	83069			CHAMBER AND TUNNEL SECTIONS
S-4	83070			BARRICADES PLAN AND ELEVATIONS
S-5	83071			BARRICADE EXAMPLE
S-6	83072			CLOSURE BLOCK EXAMPLE PLAN AND SECTIONS
S-7	83073			BLAST DOOR TYPES
S-8	83074			PLANS, SECTIONS AND DETAILS

DEFINITIVE DRAWINGS

U.S. ARMY ENGINEERING AND SUPPORT CENTER, HUNTSVILLE
HUNTSVILLE, ALABAMA

DEFINITIVE DRAWINGS
DRAWING CODE: DEF 421-80-04
UNDERGROUND AMMUNITION STORAGE FACILITY
COVER AND INDEX SHEET

1. GENERAL

a. PURPOSE/OBJECTIVE

The definitive drawings provide criteria and guidance for the planning, siting, design and construction of an underground ammunition storage facility. It was developed with particular consideration of the hazardous effects of an accidental detonation of the explosive contents of the storage chambers, and includes design features whose purpose is to contain or mitigate those effects.

b. APPLICABILITY

The definitive drawings were developed for use within continental United States (CONUS) and outside continental United States (OCONUS). For CONUS, the definitive drawings will be used as presented in conjunction with the DOD 6055.9-STD safety criteria. For OCONUS application, the definitive drawings may be modified to meet more safety-stringent host nation operational, engineering and safety requirements.

c. REFERENCE DOCUMENTS

Department of Defense (DOD)
DOD 6055.9-STD, DOD Ammunition and Explosives Safety Standards, Oct. 1992 (latest version).

2. DEFINITIONS

a. Underground Ammunition Storage Facility. An underground ammunition storage facility is a storage site located entirely below the natural ground surface (as opposed to "earth-covered" magazines). The facility is normally excavated in a solid, competent rock, and consists of one or more storage chambers that are accessed through one or more entrance passages. The principal components of an underground storage facility are defined in the glossary.

b. GLOSSARY

1). Adit - an underground passage with an entrance/exit at only one end.

2). Chamber Entrance Tunnel - a tunnel providing access into a storage chamber, either directly from the entrance portal (for a small facility) or from the storage access tunnel of a large facility.

3). Chamber Storage Site - an excavated chamber or series of excavated chambers especially suited to the storage of ammunition and explosives. A natural cavern may be subdivided or otherwise structurally modified for use as a chamber storage site.

4). Closure Block, High Pressure - a protective construction feature consisting of a massive concrete and steel block, located just inside a storage chamber, designed to seal the chamber entrance tunnel to an underground storage chamber in the event of an explosion within the chamber. MAGAE blocks are passive closures that are driven by the blast wave from a normally open to a closed position. KLOTZ blocks are active closures, operated by a hydraulic system to move from a normally closed to an open position (for access).

5). Connected-Chamber Storage Site - a chamber storage site consisting of two or more chambers connected by tunnels. Such chambers may be at the ends of branch tunnels off a main passageway.

6). Constrictions - short lengths of tunnel whose cross sectional areas are reduced to one-half or less of the normal tunnel cross section.

7). Debris (or Fragments) - any solid particle thrown by an explosion or other strong energetic reaction. For aboveground detonations, debris refers to secondary fragments, which have ballistic trajectories. For detonations in underground storage facilities, debris refers to both primary and secondary fragments, which may be transported by a strong flow of detonation gasses.

8). Debris Trap - a protective construction feature in an underground storage facility which is designed to capture fragments and debris. This is usually accomplished by relying on the inertia of the material to separate it from the detonation gas stream.

9). Entrance/Exit Tunnel - the tunnel providing access from a portal to the interior of an underground facility.

10). Expansion Chamber - a protective construction feature in an underground storage facility which is designed to reduce the airblast shock and overpressure exiting the facility by increasing the total volume of the complex. It may also function as an operating area within the underground facility, as well as a debris trap.

11). Loading Density - quantity of explosives per unit volume of storage chamber, usually expressed as kilograms per cubic meter (kg/m^3). (Note: Current U.S. safety standards (Reference 1.c. above) uses English units: i.e. pounds per cubic foot (lbs/ft^3)). As applied to underground storage facilities, there are two types of loading densities used in Quantity-Distance (QD) calculations:

a) The chamber loading density is based on the NEQ (or NEW, in english units) within an individual storage chamber and the volume of the chamber (V_{CH}). See Table 9-20 of reference, DOD 6055.9-STD.

b) The calculation of airblast peak pressures and IBD's for explosions in underground storage facilities is based on the shock-engulfed volume (V_E) of the facility. This is the total volume filled by the expanding gases at the time the blast front reaches the point of interest (e.g., the entrance to an adjacent chamber). It includes volumes in any direction that the gases can enter, to a distance from the explosion source that equals the distance from the source to the point of interest. The total loading density for a given chamber is the NEQ for that chamber divided by V_E.

12). Loading/Unloading Chamber - an interior chamber (or room) connected to the portal by an entrance/exit tunnel, where munitions are loaded on/unloaded from transport trucks and carried from/to the storage chamber by MHE.

13). Material Handling Equipment (MHE) - forklifts, dollies and other equipment used to transport munitions within the underground facility.

14). NEQ - net explosive quantity expressed in kilograms. (NEW - net explosive weight expressed in pounds).

15). Portal - an outside opening into an adit or tunnel.

16). Portal Structure - normally a reinforced concrete framework designed to provide structural support or stability to a portal.

17). Protective Construction - construction designed to protect assets or resources from damage or destruction. Protective construction with respect to underground munitions storage facilities includes:

a) Above Ground - structures designed to resist the effects of airblast and fragment/debris hazards.

b) Underground - tunnel/chamber support systems designed to resist crushing and prevent rock spall to protect stored munition assets from damage or accidental initiation and high-strength chamber doors designed to resist blast, thermal and fragment/debris loads produced by accidental detonations in adjacent storage chambers.

18). Rock Strength - Strong, moderately strong, and weak rock are designations which provide a general classification of rock types for siting underground storage facilities. Classification of a rock body into one of these three rankings is based on the rock impedance factor:

$$\text{rock impedance factor} = \rho \cdot c \cdot 10^{-6}$$

where

γ = rock density, kg/m^3

g = gravitational force, 9.76 m/sec^2

ρ = mass density of the rock, γ/g kg-sec^2/m^4

c = seismic velocity of the rock, m/sec

The rock impedance value will be 1.15 or greater for strong rock; between 1.15 and 0.75 for moderately strong rock; and less than 0.75 for weak rock.

Values of these parameters can usually be estimated based on examinations of exposed rock outcrops or core samples from an exploratory drill hole. For the detailed design of an underground storage facility (maximum span width, rock reinforcement, etc.), standard engineering classification systems for rock excavations should be used.

19). Single-chamber Storage Site - a storage chamber with its own access to the natural ground surface, not connected to any other storage chamber.

20). Spall - Spall refers to pieces of a material (and the process by which they are formed) that are broken loose from the surface of a parent body by tensile forces that are created when a compression shock wave travels through the body and reflects from the surface. For underground storage, spall normally refers to the rock broken loose from the wall of an acceptor chamber by the shock wave transmitted through the rock from an explosion in a nearby donor chamber.

21). Storage Access Tunnel - a tunnel providing access to the entrance tunnels of multiple storage chambers from another interior location, such as a loading/unloading chamber.

22). Tunnel (Chamber) Support System - construction work performed to ensure the structural stability of a tunnel or chamber, particularly the ceiling. Typical support systems (in order of increasing degrees of support provided) include:

a) Wire Mesh - a steel mesh (usually "chain link" fencing mesh) fastened to the rock surface by short rock bolts or other means to prevent the fall of small, loose pieces of rock.

b) Shotcrete - cement sprayed over the rock surface.

c) Steel Sets - steelbeams assembled into an arch shape conforming to the cross-section of a tunnel, typically spaced at one to three-meter intervals along the tunnel length. Wooden timber (lagging) may be placed between adjacent steelsets to hold back loosened pieces of rock.

d) Rockbolts - long steelrods inserted into holes drilled into the rock, connecting a steelplate (bolted onto the end of the rod) at the rock surface to an anchor point in stable rock one to five meters from the rock surface.

e) Concrete liners - reinforced concrete cast between formwork and the rock walls and ceiling of a tunnel or chamber. In rare cases, precast sections of concrete may be assembled to form a liner.

23). Tunnel - an underground passage with an entrance/exit at each end.

3. PLANNING GUIDANCE

Each underground ammunition storage facility should be designed on an individual basis, because of the wide variety of requirements or site conditions that may exist. In general, the development of a design should include the following steps:

a. Establish the storage requirement. The storage requirement refers to the hazard classification and quantity of ammunition and/or explosives that must be stored, and the associated material volume (including packaging) and net explosive quantity (NEQ). These requirements should cover the expected useful life of the facility, including possible changes in the mission of the operating organization.

b. Define the operating requirements. Like the storage requirements, operating requirements will be closely related to the mission of the operating organization, e.g., a depot, training installation, forward operating base, etc. The requirements may include the volume and rate of storage turnover, frequency of ammunition inspection or rehabilitation, rapid deployment of combat support materiel, size of ammunition containers, e.g. especially large rocket/missile containers such as MLRS pods, and the types of equipment (primarily MHE)

c. Site Selection. Selection of a specific site for the facility will depend on the availability and location of an area with the geology and topographic features required for the underground construction. Other factors will include the land use plan for a military installation, proximity to inhabited areas on or off the base, accessibility from existing roads, distance to transshipment or usage locations (e.g., firing ranges at training installations, etc).

d. Quantity-Distance (QD) Assessment. The hazard distances are based on the quantity of explosives and take into account any mitigation or suppression of the explosion effects. The minimum acceptable QD for the hazards produced by an accidental explosion within the facility should be established based on the site's proximity to inhabited buildings, public traffic routes (PTR's), airstrips, etc.

e. Site Investigation. A geotechnical subsurface investigation of the proposed site must be performed to determine the site topography, geologic structure, groundwater conditions, presence of jointing planes, cracks and fissures, and the physical properties of the material to be excavated. The results of the geological investigations will be the basis for selection of the excavation and construction methods, for selection and design of any tunnel support systems, and for provisions to be made when particular problems are expected.

f. Facility Design. After it has been determined that the site itself meets the engineering, operational and safety requirements for the facility, engineering drawings for the layout and construction of the facility can be developed. The design shall be based on applicable design standards and definitive drawings for underground storage facilities that have been approved by service and DOD safety agencies. Variances to the standard designs may be made as necessary to tailor the facility on a site-specific basis, within the limits established by the appropriate safety regulations and approved design guidelines.

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g. Establish Quantity-Distance (QD). Based on the final design of the facility and the types and NEQ of munitions to be stored and their distribution within the facility, the actual QD will be determined in accordance with procedures set forth in Chapter 9 of DoD 6055.9-STD. A final site plan for the facility which incorporates the QDs must be submitted for approval prior to construction.

4. DESIGN CRITERIA

The following design criteria for underground ammunition storage facilities, and their components, have been developed and validated by research and analysis, and have been approved by the U.S. Department of Defense Explosives Safety Board (DDESB).

a. Types of Facilities.

1). A small magazine may consist of a single storage chamber and a coaxial entrance tunnel. It may also consist of a storage chamber that is located at an angle to the entrance tunnel. See sheet S-2 for examples.

2). A large underground facility will normally have several storage chambers and more than one portal. The layout of such a facility will depend on the site, topography, geologic conditions, storage quantity/compatibility, operational needs and safety considerations. See sheet S-1 for examples.

b. Components. The underground facility layout may consist of four fundamental types of components: chambers for storage or supporting operations, interconnecting tunnels, features designed to contain or reduce the hazardous effects of explosions, and utility and other systems required for operations.

1). Facility Layouts. The layout of the entrance/exit tunnels (and any secondary access passages) and the storage chambers will be determined by the minimum tunnel length needed to obtain the required chamber cover thickness, plus any additional length needed to accommodate loading/unloading chambers, expansion chambers, etc., or to reduce the explosion hazard levels at the portals. Minimum separation distances between storage chambers are based on requirements in Chapter 9 of reference DOD 6055.9-STD. The required chamber cover thickness must be measured along the shortest direct path between a chamber boundary (roof and wall) and the ground surface, and is the larger of the two values defined below:

a) The minimum required chamber cover thickness for a structurally stable chamber is dependent on the chamber width (span), the extent of arching in the cross-section of the chamber ceiling, the chamber support system, if any, and the structural strength of the rock above the chamber.

b) The critical chamber cover thickness required to prevent a catastrophic breaching (or rupture) of the cover by a detonation of the explosive contents of the chamber is dependent on the chamber loading density. See Chapter 9 of reference DOD 6055.9-STD.

2). Portal Structures. For portal construction, the in-situ material must be removed to provide a vertical face of rock of sufficient height to allow excavation of a stable tunnel opening. A reinforced concrete portal structure is normally constructed that, for unlined tunnels, extends into the tunnel opening far enough to adjoin competent, stable rock (normally a distance of one to ten meters). The headwall and wingwalls of the portal structure should extend far enough vertically and horizontally to prevent loose rockfall onto the portal entrance area.

3). Entrance/Exit Tunnels. For stability purposes, most tunnels have an arched ceiling. The height and width of an entrance tunnel must be sufficient to accommodate the passage of the largest vehicles and ammunition containers that will enter the facility. Depending on the size of the facility, these may range from pushcarts or hand trucks to two-way traffic of large transport trucks. Generally, the dimensions of the tunnel cross-section are controlled by the required width at the tunnel springline (i.e. where the vertical portion of the wall adjoins the base of the ceiling arch). The tunnel width must accommodate the width of the largest vehicle, plus a separation distance for any two-way traffic (if required), plus maneuverability room, plus space for single-file foot traffic along one wall. See sheet S-3 for examples. The crown of the tunnel arch must also be high enough to accommodate lighting fixtures and ventilation ducts above the required clearance height of the largest vehicles. These utilities will normally be located above the tunnel springline.

4). Loading/Unloading Chambers. Large facilities may have an interior chamber for unloading or loading ammunition transport trucks. See Sheet S-1 for example. To minimize the width requirements of such a chamber, the traffic flow will normally be one-way, with vehicles entering one end of the chamber and exiting from the other end. The exit tunnel may lead to a second portal, or may loop back to intersect the entrance tunnel, with two-way traffic from that point to a single entrance/exit portal.

The width of a loading/unloading chamber must be sufficient for one lane of parked trucks, one throughlane for bypassing parked trucks, and operating room for forklifts, gantry crane with electrically operated hoist, or other MHE used to load and unload the munitions. See Sheet S-3. Since a loading/unloading chamber will be wider than the entrance tunnel, the chamber height should be that required to provide a stable ceiling arch across the width of the chamber. The required length of a loading/unloading chamber will depend on the number of vehicles expected to be parked at any one time, plus the extra distance needed to pull into or out of a parking space.

5). Storage Access Tunnels. In large facilities, storage access tunnels lead from loading/unloading chambers (or other internal rooms) to the storage area (see sheet S-1). As an alternative, the storage access tunnel may be designed to allow transport trucks to be loaded or unloaded in front of the individual chamber entrance tunnels. In these facilities, the storage access tunnel must be designed like an entrance/exit tunnel.

6). Chamber Entrance Tunnels. Chamber entrance tunnels will normally be used only by hand trucks, dollies, or forklifts for moving munitions from the storage access tunnel or from the loading/unloading chamber to the individual storage chambers. The widths of these tunnels are based on the width of the MHE and/or large ammunition containers plus a separation distance for two-way traffic, plus maneuverability room, plus space for single-file foot traffic. The height of these tunnels must be based on the height of the MHE, particularly a forklift in the raised, transporting position. Again, adequate heights must be allowed for lighting and ventilation ducts above the equipment height.

7). Storage Chambers.

a) The size and shape of the munition storage chambers are based on the allowable NEQ per chamber, the bulk volume of the munitions, and the engineering properties of the rock in which a chamber is excavated. For munitions such as rockets and missiles, the bulk volumes will be many times greater than those of munitions with large explosive weights, such as 155mm M107 artillery projectiles. The required floor area of a storage chamber will also depend on the "stackability" of the packaged munitions and the operating room required by the MHE that stacks them.

b) A reasonable minimum chamber width to accommodate stacking space and MHE maneuver room is about 10 meters. The maximum chamber width is normally limited by the free span width that can be excavated in the rock and remain structurally stable. Chamber widths of 20 to 30 meters can be constructed in very strong rock types, but the ceiling heights required to provide a stable arch results in excavation volumes that increase roughly as the square of the chamber width. From an engineering standpoint, there is essentially no limit to the chamber length that can be excavated. Consequently, chambers with large storage capacities may have lengths up to six or eight times the chamber width, in order to maximize the storage volume while maintaining a stable chamber.

c. Hazard Reduction Features. Hazard reduction features are designed to contain or mitigate the hazardous effects of an explosion, such as airblast, debris (fragments), and thermal effects. The use of one or a combination of these control features will greatly reduce the external hazards. Use of barricades in conjunction with any other hazard reduction feature will lower the debris hazard to a level where QD considerations for debris will not be required.

1). Barricades

a) A barricade, if required, shall be located in front of a portal and centered on the extended axis of the tunnel. The face of the barricade toward the portal shall be vertical and concave in plan. The barricade shall have a vertical face, oriented perpendicular to the tunnel axis, with wingwalls on either side of the face that are angled at 30 to 60-degrees toward the portal. The width of the barricade face (excluding wingwalls) shall intercept an angle of at least ten degrees to the right and left of the extended tunnel width. The height of the barricade along its entire width shall intercept an angle of at least ten degrees above the extended height of the tunnel. See Sheet S-4 for barricade orientation.

b) The barricade shall be located a distance of not less than one and not more than three tunnel widths from the portal. The actual distance should be no greater than that required to allow passage of any vehicle or material handling equipment (MHE) that may need to enter the tunnel. The distance shall be based on the turning radius and operating width required for the vehicle, or MHE.

c) The front face of the barricade (excluding wingwalls) shall be constructed of reinforced concrete, with a minimum thickness of 0.305 meters or a thickness equal to 10 percent of the barricade height, whichever is greater. The concrete wall shall have a spread footing of sufficient width to prevent significant settlement, and the central wall, wingwalls, and footing must be structurally tied together to provide stability. See Sheet S-5 for example of a barricade design. The backfill behind the concrete wall may be composed of any fill material, including rock rubble from the tunnel excavation, with a maximum particle size of 150mm within the area extending out to three feet from the rear face of the wall. An engineering analysis should be performed to ensure that the barricade will remain in place based on the maximum shock wave from a storage chamber detonation that exits a tunnel portal.

2). Debris Traps.

Debris traps are pockets excavated in the rock at or beyond the end of tunnel sections, and are designed to entrap debris blown through the tunnel from an explosion. The total volume of all debris traps and expansion chambers between a storage chamber and any portal should be sufficient to contain the full potential volume of debris from a detonation in that storage chamber. Debris traps should be at least 20 percent wider and 10 percent taller than the tunnel leading to the trap, with a depth of at least one and a half times the tunnel diameter.

3). Expansion Chambers.

Expansion chambers are large rooms located between the storage chamber(s) and the tunnel entrance(s), having a cross-sectional area at least three times as great as that of the largest tunnel intersecting the expansion chamber, and a length that is at least as great as the expansion chamber width. For the chamber to be effective in entrapping debris, the tunnels entering and exiting the chamber must be offset in axial alignment by at least two tunnel widths, or enter and exit the chambers in directions that differ by at least 45 degrees.

4). High-pressure Closures.

High pressure closures are large blocks constructed of steel, concrete and/or other materials, that can obstruct or greatly reduce the flow of the airblast and debris from an explosion in a storage chamber. The block must be designed to remain structurally intact and of sufficient mass to obstruct the outflow of airblast following an explosion in that chamber to reduce pressures in the connecting tunnels. A design analysis for the closure block must be provided to DDESB for approval. The two closure block concepts that have been tested are:

a) MAGAE Block. This block is designed to be rapidly driven from an open to a closed position by the detonation pressures in the chamber. Because the block is normally in an open position, a blast door must be provided at the entrance to the storage chamber to provide protection from an explosion elsewhere in the facility. See Sheet S-6 for an illustration of the MAGAE block configuration.

b) KLOTZ Block. This block is designed to be moved by mechanical mechanisms from closed-to-open and open-to-closed position. The block is in the closed position during long term storage. The block is in the open position when operations are being performed in the storage chamber and will rapidly close in the event of an explosive accident. A blast door is not required with this type of closure, as the block is normally in the closed position.

5). Tunnel Constrictions. A constriction is a short section of tunnel with a reduced cross-section. The minimum length of a constriction is 1.5 times the tunnel diameter. If located within five (5) tunnel diameters of a portal, a constriction reduces the external airblast by providing a smaller hydraulic diameter of the exit, as used in the equation for external overpressure in Chapter 9 of reference DOD 6055.9-STD. Constrictions may also be located at chamber entrances to reduce the size of blast doors or closure blocks, but do not contribute to hazard reduction at these locations.

6). Blast Doors. To prevent propagation and protect assets, blast and fire resistant doors shall be provided within multichambered facilities (except as noted above). The design load for all blast doors should be based on the maximum airblast pressure and impulse at the door location, as calculated using the computer program BLASTX, or an equivalent code approved by the DDESB. The BLASTX computer program may be obtained from US Army Engineer Waterways Experiment Station, CEWES-SD, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199. A blast door is normally provided by a single manufacturer as a complete assembly including the door, frame, hardware, and accessories. U.S. Army Corps of Engineers Guide Specification for Military Construction, CEGS-13977, Blast Resistant Doors, should be included as a performance specification of individual door assemblies, the door type, blast effects, rebound, deformation limits, operating forces, hardware, and accessories. Discussed below are some of the blast door requirements.

a). Door Size and Type. The doors shall be large enough to accommodate the passage of the MHE and/or the ammunition container. Door types available include single leaf, double leaf or sliding doors.

b). Blast Door Material. Selection of material shall be based on availability, operability and economics. Steel, concrete, or hollow metal doors may be used, based on the blast-induced loading.

c). Performance Criteria. Furnish blast door assembly and frame to meet the triangular pressure-time loading.

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Peak blast pressure, P_r, in MPa
Duration of blast pressure, t_r, in milliseconds (ms)
Total impulse, $I_r = P_r \cdot t_r/2$ MPa-ms
Allowable deflection shall be within elastic limits.
Door shall be designed to be fully operable after an incident in an adjacent storage chamber.
Door shall be designed for 100 percent rebound.
Dynamic increases of 10 percent may be used for material allowances.
Safety factor shall be 1.0.

d). Example of Triangular Pressure-Time Loading

d. Operations Support Systems

1). Ground Water Control Requirements. The drainage system required will depend on the design of the facility, its depth, ground water conditions, and the local surface hydrology. Ground water and surface hydrology surveys and investigations should be performed as part of the initial site investigations.

a). Leakwater control of storage chamber. A waterproofing system which does not permit leakage must be applied to storage chamber design. Recommended alternatives for water proofing include a concrete lining with water proof materials, construction of a waterproof inner structure, or installation of water proof plastic fabric liner. The space between the excavated rock surface and a water proof structure should be 0.6m minimum to allow inspection and maintenance of the structural walls and the liner.

b). Drainage System. Drainage from tunnels and storage chambers shall be by gutters, sloped 2% minimum and located at or near the base of tunnel or chamber walls. An open grating shall be installed over the gutter or, for larger gutters, the gutter volume may be filled with a coarse graded crushed rock. Drainage from these areas may require a sump and pump, depending of the location of the outlet end. See drainage gutter details on Sheet S-8.

2). Humidity Control Requirements. The relative humidity requirement in the storage chambers should be based on the ammunition and equipment being stored. The relative humidity level should be at 55% or less. The rise in the humidity level by inflow of outside humid air should be recovered within 24 hours by a central humidity control system, or separate control systems. A humidity sensor, which controls dehumidifier operation, must be placed in each chamber to continuously monitor the chamber air conditions.

3). Ventilation System. Design of a ventilation system should be based on applicable health and safety regulations for underground operations, on the overall facility layout, and the types of loading/unloading equipment and transportation vehicles that will operate in the facility. For a large storage facility, one or more vertical shafts to the surface may be required provide intake or exhaust ventilation paths.

a). Natural Ventilation. Two exits in opposite directions at different elevation levels can contribute to good natural ventilation.

b). Mechanical Ventilation. Types of ventilation systems that could be designed are ducts for air supply and exhaust, jet fan, concentrated exhaust shaft, etc. Any mechanical ventilation system to be used in the tunnel should be designed to allow a change of air flow direction in the case of an emergency.

4). Electrical Requirements. Minimum requirements are contained in Chapter 6 of reference DOD 6055.9-STD.

a). Lighting Fixtures. Lighting fixtures, i.e. sodium or metal halide lamps, should be designed for durability and ease of maintenance. All fixtures should be explosion-proof and fire resistant. The fixtures should be located as to not interfere with operation of equipment.

b). Illumination. Tunnels shall have adequate illumination for loading/unloading operations based on applicable regulations.

c). Emergency Exit Lighting System. Water proof emergency exit lights and/or signs should be located at 20-30m intervals and at turning points in all tunnels and chambers.

5). Fire Detection/Control Systems. Fire alarm and fire suppression systems must be designed to detect and alarm automatically. Systems installed in areas where dehumidifier systems are not available should have operating parts which are corrosion-resistant. Quantity and types of fire detectors, sprinklers, foam sprayers, etc., should be determined based on control area, installation height, and fire protection policies.

6). Construction Materials. Construction materials, including ventilation and utility ducts, to be used in ares where dehumidifier systems are not available, shall be corrosion resistant.

7). Finish of Rock Surface and Tunnel Floor. Rock surfaces should be reinforced by shotcrete or other appropriate methods to prevent damage to personnel, ammunition, or equipment by loose rock. Pavement materials of tunnel/adit floor should be carefully selected to minimize small particles/dust caused by transport vehicles and MHE.

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TABLE 1
CLASSIFICATION OF ROCK TYPES FOR EXPLOSIVES SAFETY SITING OF UNDERGROUND MAGAZINES

STRENGTH CLASS	ROCK PROPERTIES: MASS DENSITY, kg·sec²/m⁴	ROCK PROPERTIES: IN-SITU SEISMIC VELOCITY, c m/sec	ROCK PROPERTIES: IMPEDANCE FACTOR $\rho \cdot c \cdot 10^{4}$ kg·sec /m³
WEAK	< 225	< 3,400	< 0.75
MODERATELY STRONG	225 - 250	3,400 - 4,600	0.75 - 1.15
STRONG	> 250	> 4,600	> 1.15

TABLE 2
CLASSIFICATION OF ROCK TYPES FOR DESIGN AND CONSTRUCTION OF UNDERGROUND MAGAZINES

STRENGTH CLASS	SYSTEM VALUES: RQD	SYSTEM VALUES: RMR	SYSTEM VALUES: Q
WEAK	< 50	< 40	< 5
MODERATELY STRONG	50 - 80	40 - 70	5 - 50
STRONG	> 80	> 70	> 50

ROCK CLASSIFICATION TABLES:

The tables were developed to provide definitions of the classification of rock types for siting, design and construction of underground magazines per Chapter 9 of the referenced safety standard, DOD 6055.9-STD.

1. Rock Classification for Safety Siting.

   a. The rock classifications are used to determine the chamber separation and ground shock distances based on shock impedance as a basis for classifying weak, moderately strong, and strong rock.

   b. The basic rock type and approximate density can be determined from local rock outcrops and from rock cores taken from an exploratory drill hole.

   c. Seismic velocities are established from a seismic survey of the area.

2. Rock classification for Design and Construction of Underground Magazines.

   a. A geologic investigation must be conducted to acquire information on rock properties and the local geologic structure of a proposed underground magazine site for developing detailed designs and construction planning.

   b. The geologic conditions (particularly the orientation, spacing and frequency of the joints and bedding planes that control the shape and size of rock blocks) serve as a basis for classifying the rock, for determining rock loads on steel set supports or concrete reinforcement elements, for determining shotcrete thickness and for selecting the support system itself. The frequency of joints and fractures and their characteristics will affect the stability of an excavation, and the requirement for structural reinforcement of the rock to increase stability.

   c. The Rock Mass Rating (RMR) or the Q System is used for classification of weak, moderately strong, and strong rock at all proposed sites for design and construction of underground magazines.

   d. Rock Quality Designation (RQD) is an engineering classification system for rock based on the number of fractures (or joints) per meter of a length of rock core.

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ROCK CLASSIFICATION TABLES

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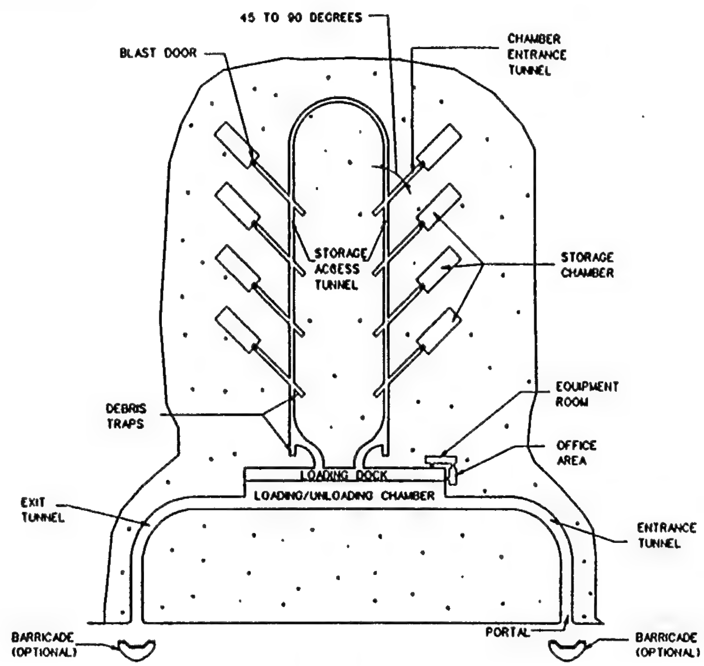
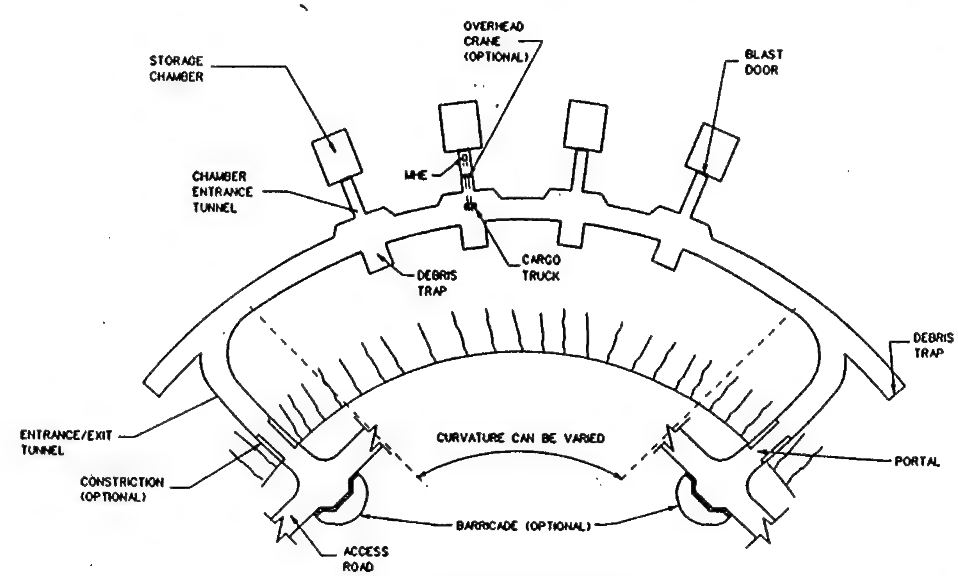
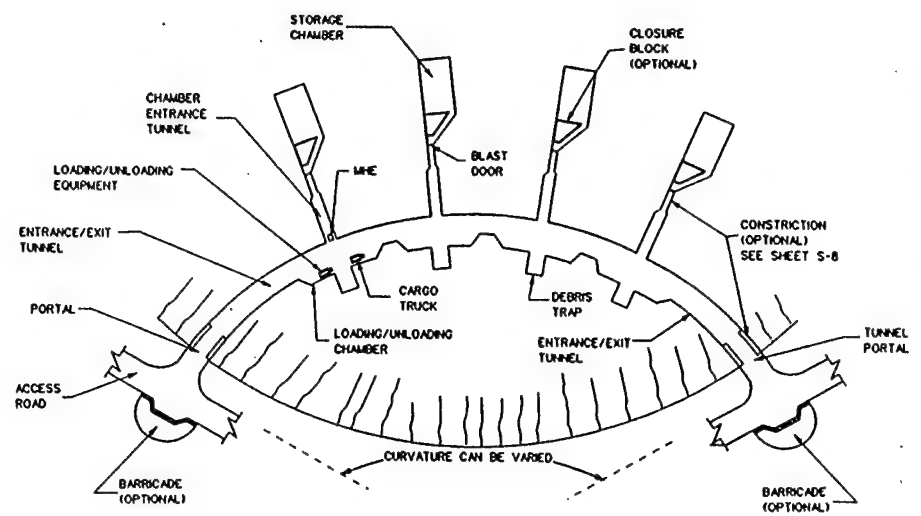


TYPICAL LARGE FACILITY



TYPICAL LARGE FACILITY



TYPICAL LARGE FACILITY

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DEFINITIVE DRAWINGS
UNDERGROUND AMMUNITION STORAGE FACILITY
LARGE FACILITY LAYOUT

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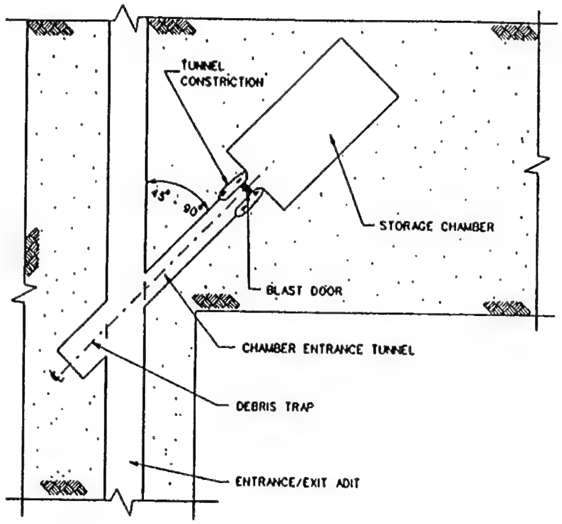
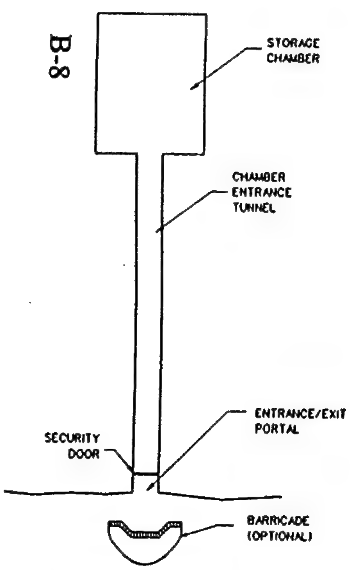
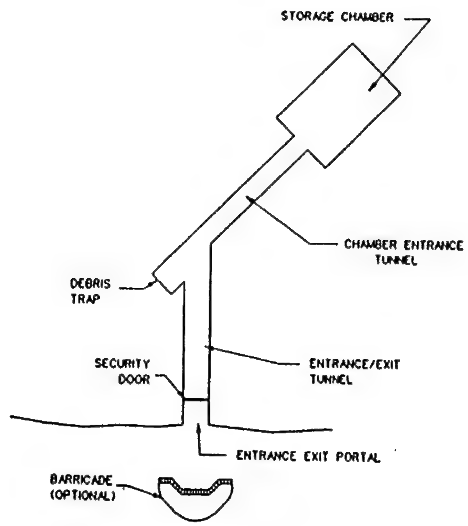


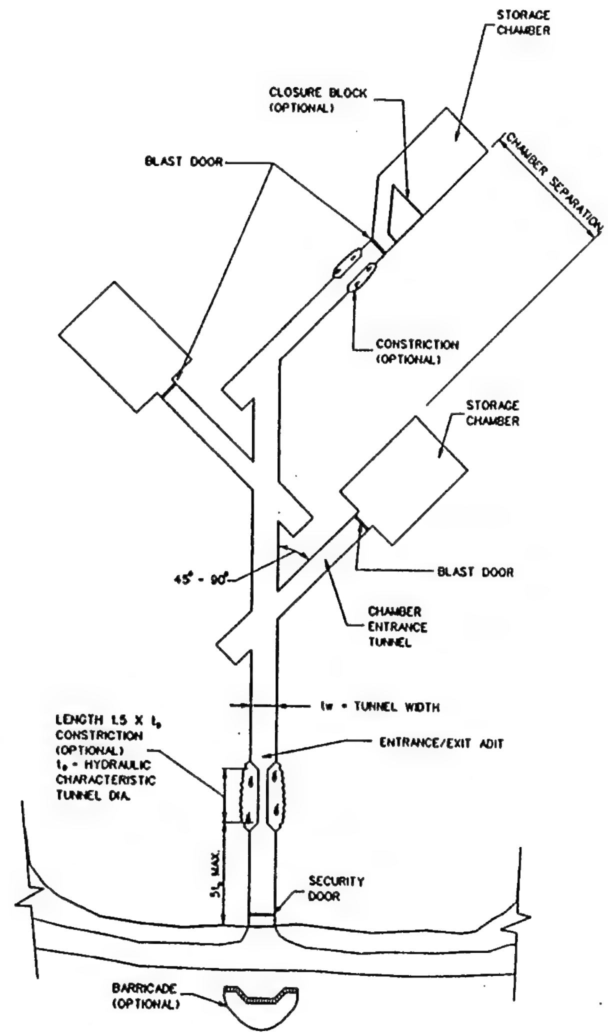
TYPICAL STORAGE CHAMBER DESIGN



SINGLE (SHOTGUN) STORAGE FACILITY
(TYPICAL LAYOUT)



SINGLE STORAGE FACILITY
(TYPICAL LAYOUT)



MULTI-CHAMBER STORAGE FACILITY
(TYPICAL LAYOUT)

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DEFINITIVE DRAWINGS
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SMALL FACILITY LAYOUT

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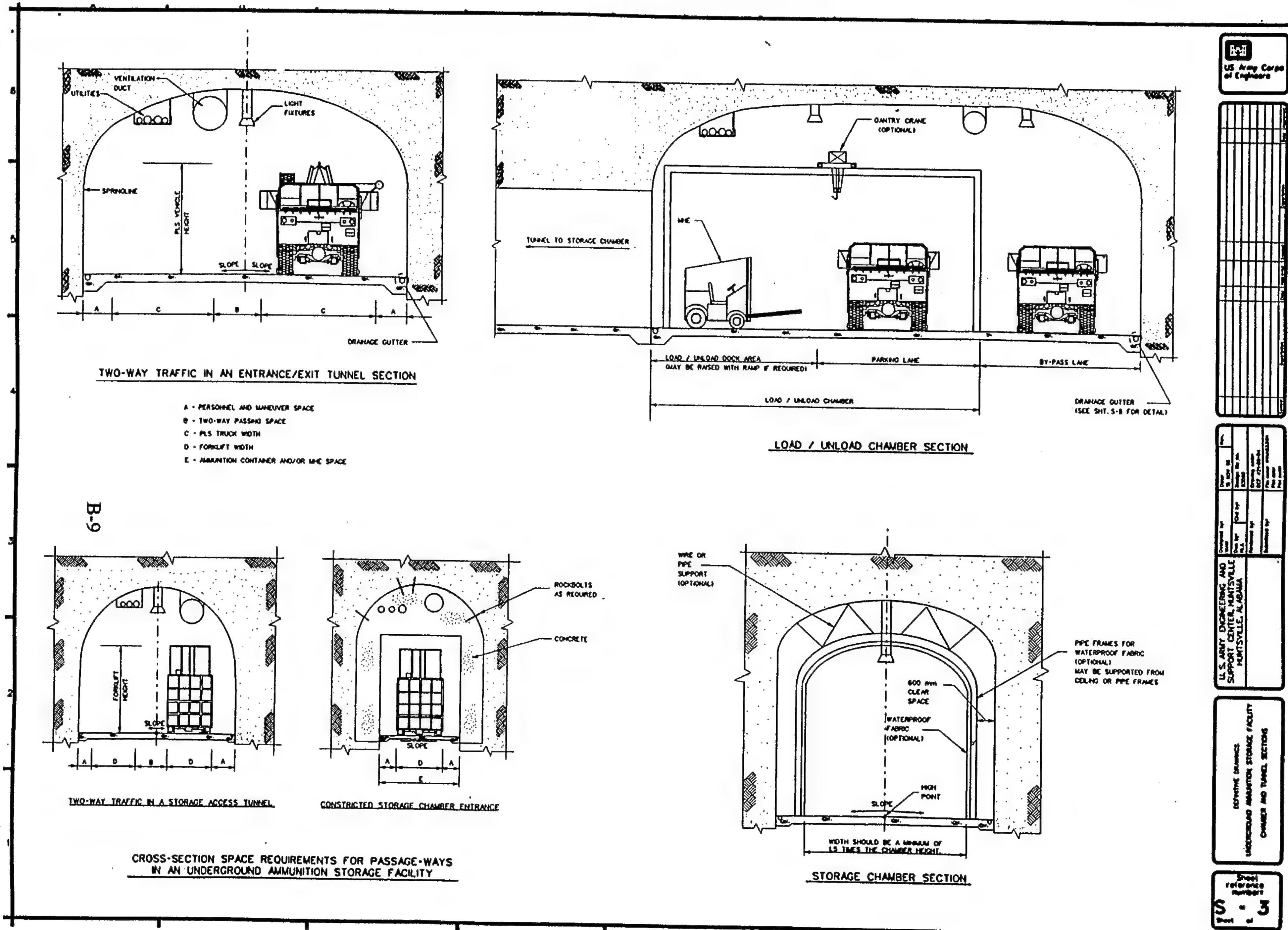

VENTILATION DUCT
UTILITIES
LIGHT FIXTURES
SPRINGLINE
PLS VEHICLE HEIGHT
SLOPE
SLOPE
A
C
B
C
A
DRAINAGE GUTTER
TWO-WAY TRAFFIC IN AN ENTRANCE/EXIT TUNNEL SECTION
A - PERSONNEL AND MANEUVER SPACE
B - TWO-WAY PASSING SPACE
C - PLS TRUCK WIDTH
D - FORKLIFT WIDTH
E - AMMUNITION CONTAINER AND/OR MHE SPACE
GANTRY CRANE (OPTIONAL)
MHE
TUNNEL TO STORAGE CHAMBER
LOAD / UNLOAD DOCK AREA (MAY BE RAISED WITH RAMP IF REQUIRED)
PARKING LANE
BY-PASS LANE
LOAD / UNLOAD CHAMBER
DRAINAGE GUTTER (SEE SHT. S-8 FOR DETAIL)
LOAD / UNLOAD CHAMBER SECTION
FORKLIFT HEIGHT
SLOPE
A
D
B
D
A
TWO-WAY TRAFFIC IN A STORAGE ACCESS TUNNEL
ROCKBOLTS AS REQUIRED
CONCRETE
SLOPE
A
D
A
E
CONSTRICTED STORAGE CHAMBER ENTRANCE
CROSS-SECTION SPACE REQUIREMENTS FOR PASSAGE-WAYS IN AN UNDERGROUND AMMUNITION STORAGE FACILITY
WIRE OR PIPE SUPPORT (OPTIONAL)
PIPE FRAMES FOR WATERPROOF FABRIC (OPTIONAL) MAY BE SUPPORTED FROM CEILING OR PIPE FRAMES
600 mm CLEAR SPACE
WATERPROOF FABRIC (OPTIONAL)
HIGH POINT
SLOPE
WIDTH SHOULD BE A MINIMUM OF 1.5 TIMES THE CHAMBER HEIGHT.
STORAGE CHAMBER SECTION
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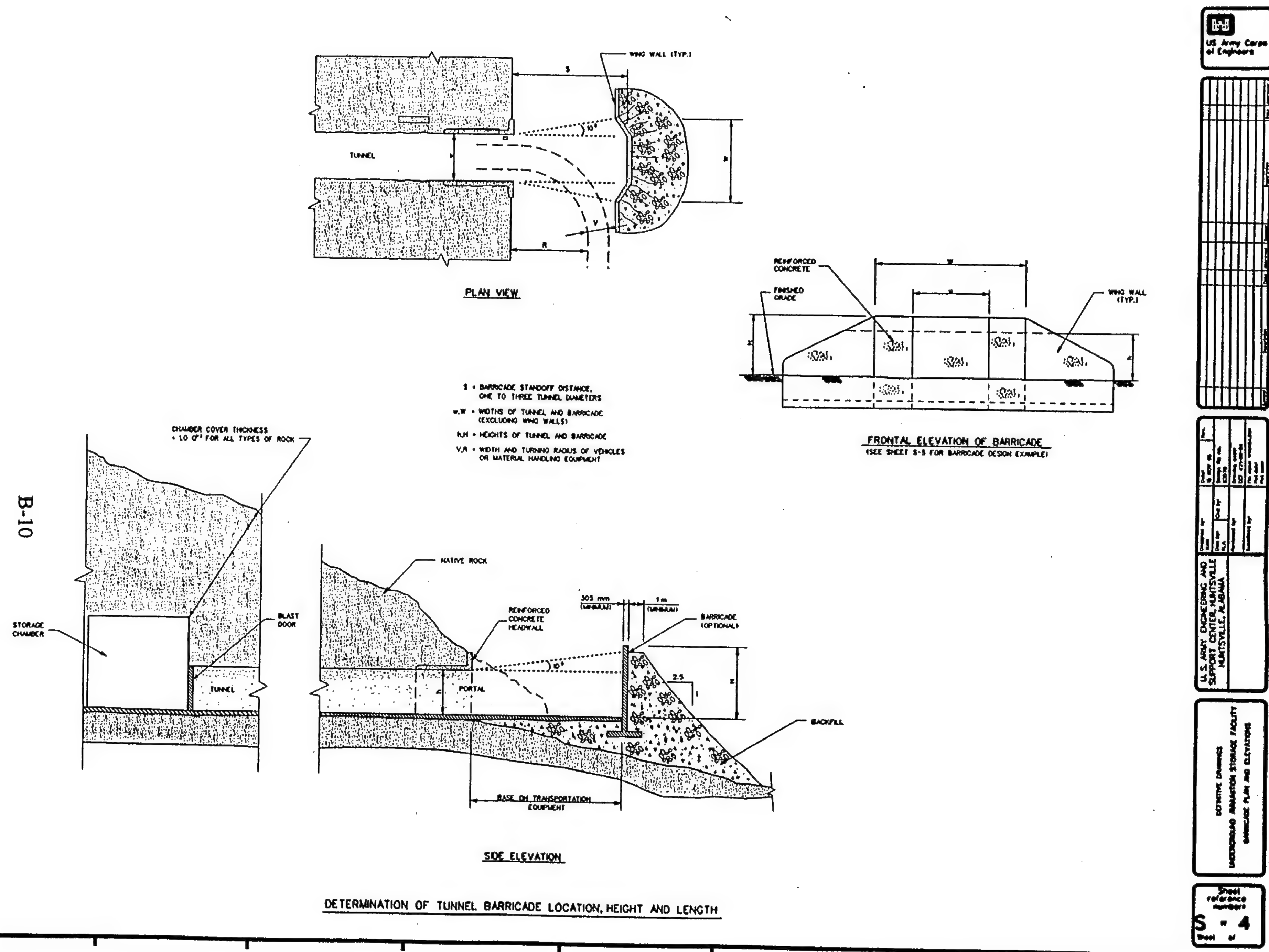
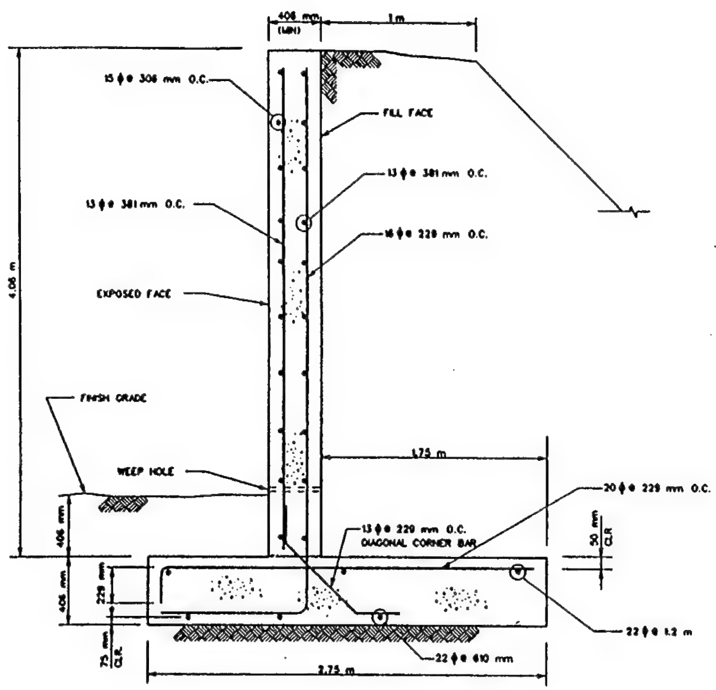
DEFINITIVE DRAWINGS
UNDERGROUND AMMUNITION STORAGE FACILITY
CHAMBER AND TUNNEL SECTIONS
Sheet reference number
S - 3



DETERMINATION OF TUNNEL BARRICADE LOCATION, HEIGHT AND LENGTH



BARRICADE EXAMPLE

DESIGN EXAMPLE OF A BARRICADE

1. Reference: Concrete Reinforcing Steel Institute,(CRSI), 1984

2. Assumptions:

a. Assume Class B soil which includes granular soils, mixed grain sizes, dense enough to cause low permeability. Weight of soil is 2162 kilograms per cubic meter.

b. Level backfill with no surcharge.

c. Determine height of wall, h_w, from top of base or footing to top of wall.

1). Tunnel entrance height = 3.12m

2). Barricade standoff distance = 3.0m

3). Additional height required based on paragraph 5.C.5. and Figure 5-4 of reference DOD 6055.9-STD.

Additional height = 3.0 × tan 10° = 0.53m

4). Top of base located 0.41m below finish grade.

5). Total height of wall, h_w = 3.12 + 0.53 + 0.41 = 4.06m

d. Wall thickness, t_w is the greater of 0.3m or $0.1h_w$ as per Chapter 5 of reference DOD 6055.9-STD.

$$t_w = 0.1 \times 4.06m = .406m > 0.3m$$

e. Concrete shall develop compressive strength, fc' = 28MPa in 28 days.

f. Reinforcing steel shall be ASTM A-615M, Grade 400.

3. Solution: From CRSI reference.

a. Heel length = 1.75m
b. Base depth = 406mm
c. Base width = 2.75m
d. No key required
e. Diagonal corner bars = 13 ϕ @ 229mm on-center
f. Base reinforcement
   1). Top Bars = 19 ϕ @ 229mm on-center
   2). Longitudinal Bars
      a). Top = 22 ϕ @ 1.22m on-center
      b). Bottom = 22 ϕ @ 610mm on-center
g. Wall (Stem)
   1). Fill Face
      a). Vertical Bars = 16 ϕ @ 229mm on-center
      b). Horizontal Bars = 13 ϕ @ 381mm on-center
   2). Exposed Face
      a). Vertical Bars = 13 ϕ @ 381mm on-center
      b). Horizontal Bars = 16 ϕ @ 279mm on-center

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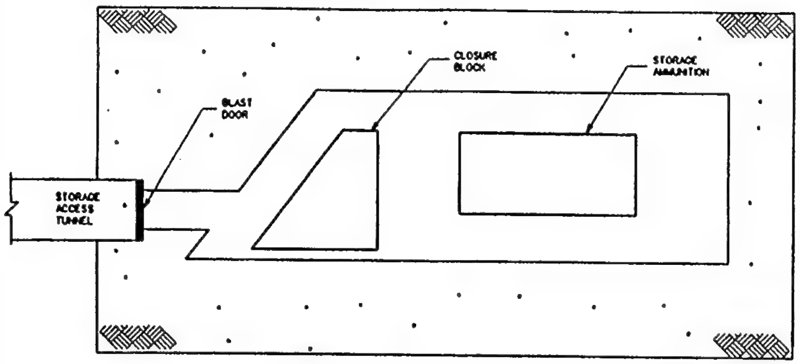
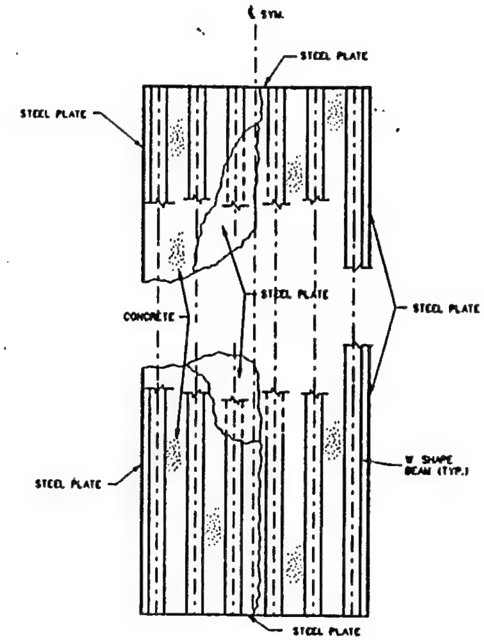
DEFINITIVE DRAWINGS
UNDERGROUND AMMUNITION STORAGE FACILITY
BARRICADE EXAMPLE

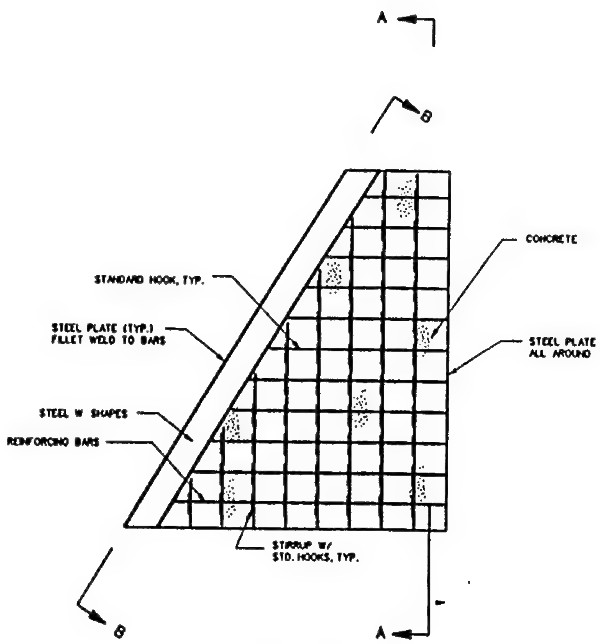
Sheet reference number S-5



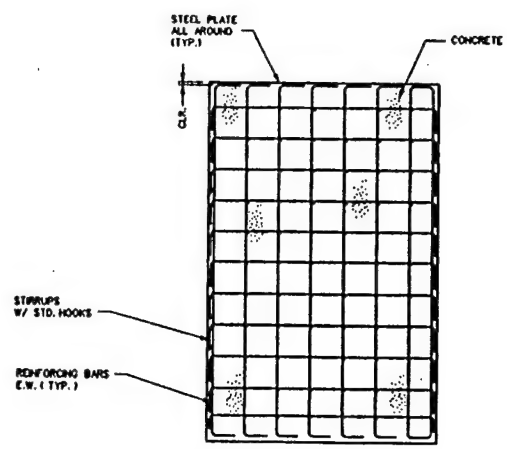
STORAGE CHAMBER PLAN



SECTION B-B



CLOSURE BLOCK PLAN



SECTION A-A

GENERAL NOTES

1. THE CLOSURE BLOCK CONFIGURATION SHOWN ON THIS SHEET IS FOR ILLUSTRATION ONLY. ENGINEERING ANALYSIS IS REQUIRED.
2. LENGTH, WIDTH, HEIGHT, MASS AND STRUCTURAL STABILITY IS TO BE DETERMINED BASED ON THE SIZE OF THE OPENING AT THE STORAGE CHAMBER ENTRANCE, SIZE OF THE STORAGE CHAMBER AND THE LOADING DENSITY.

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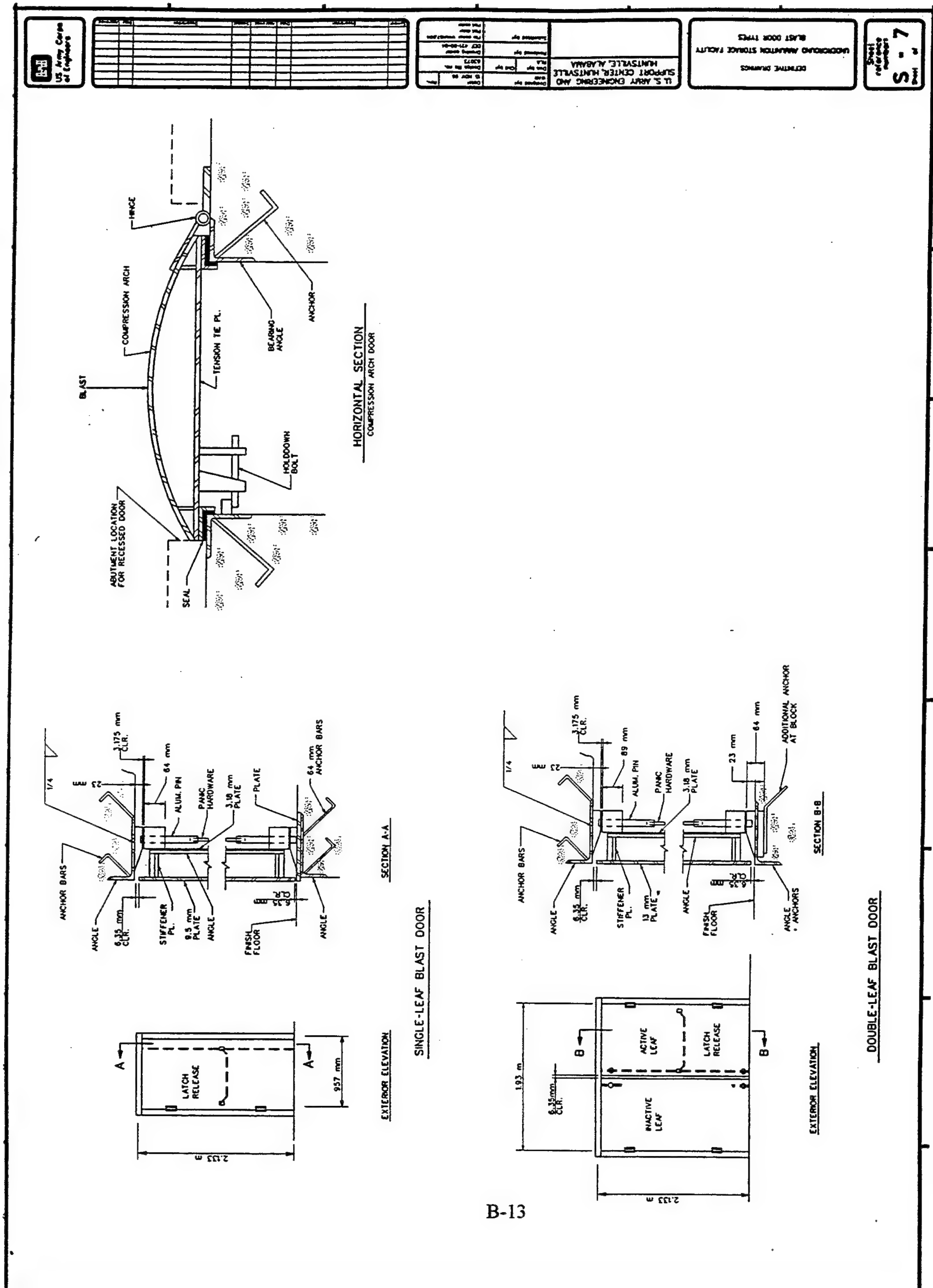
DEFINITIVE DRAWINGS
UNDERGROUND AMMUNITION STORAGE FACILITY
CLOSURE BLOCK EXAMPLE, PLAN & SECTIONS

Sheet reference number:
S - 6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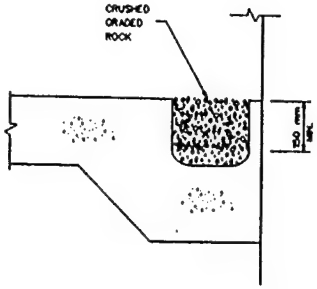
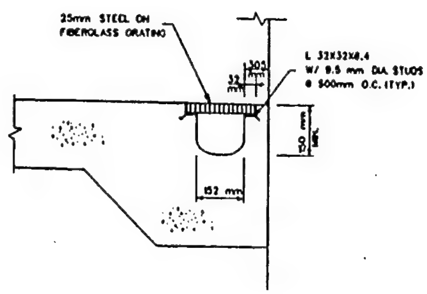
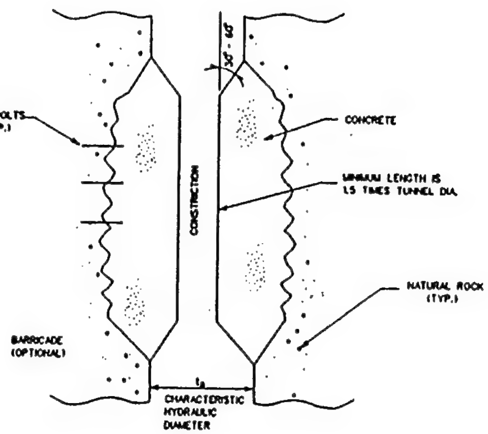
DEFINITIVE DRAWINGS
UNDERGROUND AMMUNITION STORAGE FACILITY
BLAST DOOR TYPES
S - 7
HORIZONTAL SECTION
COMPRESSION ARCH DOOR
BLAST
COMPRESSION ARCH
TENSION TIE PL.
HINGE
BEARING ANGLE
ANCHOR
HOLDDOWN BOLT
ABUTMENT LOCATION FOR RECESSED DOOR
SEAL
SINGLE-LEAF BLAST DOOR
EXTERIOR ELEVATION
LATCH RELEASE
957 mm
2.133 m
SECTION A-A
ANCHOR BARS
ANGLE
6.35 mm CLR.
STIFFENER PL.
9.5 mm PLATE
FINISH FLOOR
3.175 mm CLR.
23 mm
64 mm
ALUM. PIN
PANIC HARDWARE
3.18 mm PLATE
PLATE
64 mm ANCHOR BARS
DOUBLE-LEAF BLAST DOOR
ACTIVE LEAF
INACTIVE LEAF
1.93 m
SECTION B-B
13 mm PLATE
89 mm
ADDITIONAL ANCHOR AT BLOCK
ANGLE + ANCHORS



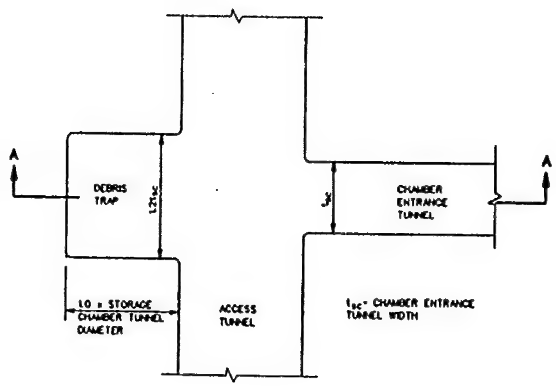
DRAINAGE GUTTER DETAIL (OPTIONAL)



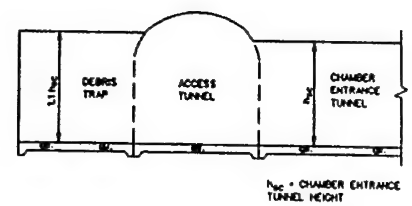
DRAINAGE GUTTER DETAIL



TYPICAL CONSTRICTION PLAN



DEBRIS TRAP PLAN



SECTION A-A

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DEFINITIVE DRAWINGS
UNDERGROUND AMMUNITION STORAGE FACILITY
PLANS, SECTIONS AND DETAILS

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The objective of the UAST Program was to develop improved underground magazine designs which could significantly reduce the existing Quantity-Distance (Q-D) hazard ranges from accidental detonations. The program involved coordinated research efforts by the U.S. and Korea, including small- and intermediate-scale experiments, computer modeling, and various supporting studies. This report presents an overview of the research effort and evaluates the effects of various underground magazine design features (debris traps, expansion chambers, closure devices, constrictions, barricades, etc.) on external hazards (airblast, debris, and ground shock) produced by accidental detonations in underground storage facilities.

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